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RECOVERY OF SENSIBILITY AND SUDOMOTOR ACTIVITY IN THE HAND AFTER NERVE SUTURE

BY

LARS ÖNNE

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RECOVERY OF SENSIBILITY AND SUDOMOTOR ACTIVITY IN THE HAND AFTER NERVE SUTURE

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STOCKHOLM 1962

Translated from the Swedish

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INTRODUCTION

It is only in comparatively recent years that the importance of sensibility to the function of the hand has come to be realised. The earlier tendency to underestimate the sequelae of sensory disturbances is probably due in some measure to the fact that a loss of sensibility does not immediately produce such obvious symptoms as a disturbance of the motor function.

The importance of sensibility to the function of the hand is reflected to some degree in the Swedish compensation rates. A complete median nerve lesion is at present rated as a 25 per cent invalidity compared with 60 per cent for loss of the whole hand.

While no data are available on the incidence of nerve injuries in Sweden, it is known that during the First World War 15 per cent of all extremity injuries among the American troops involved the nerves (Bunnell, 1948).

Despite numerous recent follow-up studies on nerve injuries (e. g. Seddon *et al.*, 1954; Woodhall & Beebe, 1956; Nicholson & Seddon, 1957; Stromberg *et al.*, 1961), it is still uncertain to what extent sensibility may return in the hand following a nerve suture performed under ideal conditions. Nor is it known what optimal results are obtainable with a nerve suture. In the absence of this knowledge it is impossible to assess the effect of various factors on the end result.

The investigation reported in this monograph consists of a follow-up study of selected cases in which the author attempted to asses the extent to which sensibility returns in the hand after nerve sutures performed under favourable conditions—what will be referred to as "ideal" nerve sutures. Interest has been centered on the fine discriminative sensibility because it is of fundamental importance to the function of the hand. Particular attention has also been devoted to sweat secretion, since this has been said to be related under certain circumstances to the functional value of the sensibility in the hand (Moberg, 1958) and therefore may be used as an objective index of this quality of sensibility.

VARIATION IN CUTANEOUS INNERVATION OF THE FINGERS

As regards the function of the hand it is chiefly the volar sensibility that is of importance. The volar surface is innervated by the median and ulnar nerves; the boundary between these two territories usually passes down the middle of the ring finger but there may be a shift in either direction so that the volar aspect of the ring finger is supplied entirely by one nerve. In 3—4 per cent of Stopford's series (1918) the region served by the ulnar nerve also included the ulnar half of the middle finger (Fig. 1). On the thumb the borderline between the radial and median fields varies, sometimes passing more or less volar to the midlateral line (Moberg, 1960 B). The index finger is consequently the only one the whole volar surface of which is always supplied by the median nerve; moreover, the little finger is invariably innervated by the ulnar nerve. In low ulnar lesions the dorsal cutaneous branch remains intact and the sensibility is then retained dorsally on the proximal phalanx of the little finger, and sometimes even as far as the distal phalanx. In these low ulnar nerve injuries the volar surface of the little finger is always totally anaesthetic, at least for light touch (Head & Sherren, 1920; Foerster, 1929).

Fig. 1 Range of variation of the median nerve field.

TESTS OF SENSIBILITY

The sensibility of the hand varies from one area to another. The fine sensibility of the pulps enables ut to recognize what we are touching without the aid of sight. This complex quality has been referred to as tactile gnosis (Broman, 1945 A). A hand without tactile gnosis is "blind", and is useless without the aid of vision (Moberg, 1958). For this reason it is essential that every examination of the sensibility in the hand shall include a test of tactile gnosis.

The tests used to study sensibility may be divided into three groups, namely the examination of (i) the four "primary" modalities, (ii) tactile gnosis, and (iii) sweat secretion.

EXAMINATION OF THE FOUR MODALITIES

At the end of the last century it was demonstrated that the sensibility was not evenly distributed on the skin surface, but that there was a mosaic pattern of tiny spots which reacted to varmth, cold, touch or pain (Blix, 1884,1885; von Frey, 1894—96). As a logical consequence of these findings a complete examination of sensibility came to imply the testing of these four modalities.

This division of sensibility in modalities has been subjected to much criticism especially with the deepening of our knowledge of the finer innervation of the skin. Each point of the skin has a multiple innervation. There are no morphologically specific nerve terminals in the human skin serving each of the four modalities (Weddell 1941 A, B, 1945; Sinclair *et al.*, 1952; Hagen *et al.*, 1953; Weddell *et al.*, 1955). In 1946 it was stated by Bishop that the sensibility tests should be freed from the concept of sensory modality. Noordenbos (1959, 1960) found it difficult to see why touch should be regarded as a primary sensory modality. "It would appear that the concept of the 'four sensory modalities' ... is the results of incorrect verbalization of our clinical findings". He points out, morover, that there is often confusion between stimuli and sensation, the latter of which is a central phenomenon. Moberg (1962) seems to be thinking along similar lines when he writes of testing schemes that they "are constructed more according to the examining methods than on physiologic principles".

What information is then to be obtained from an examination of the four modalities after a nerve suture?

Cold and warmth

Most workers (e. g. Seddon, 1954; Moberg, 1962; Sakellarides, 1962) maintain that examination of these qualities is of little value. Most reports contain no information on these modalities.

Touch

Examination of the sense of touch is an integral part of all follow-up studies. With regard to the ambivalent term 'touch' it should be noted that the stimuli used by various workers for testing this sense are by no means uniform. Cotton wool is commonly employed; some prefer a strip of paper while others stroke the skin with the finger. In an attempt to standardize the technique von Frey (1894) used graduated series of hairs mounted on a handle, which exerted different pressures when they began to bend. von Frey maintained that it was the pressure on unit area that was the critical factor, and accordingly calculated all the values as pressures per square millimetre. While this principle may seem *a priori* correct it is open to certain objections. Any perception of touch on the fingers implies a deformation of the skin surface (Cauna, 1954). Lindblom (1958) and Höglund & Lindblom (1961), who recorded action potentials from thin filaments of the dorsal root on toads, demonstrated that a certain deformation of the skin surface is required before impulses are elicited. A thicker hair not only exerts a greater pressure, but it also displaces a greater area of skin so that a greater number of receptors will be stimulated (Guilford & Lovewell, 1936). Compared with the size of the deformed area, the area of contact of the hair will be of minor importance. This has been confirmed by Goldberg, who in tests of corneal sensibility found that it was the absolute pressure that was the determining factor and not the diameter of the hair. Pontén (1960) avoided these problems by using hairs of the same calibre but loading them with different weights. However, the design of his apparatus required the hair always to be held vertical.

Only a few workers have mentioned what they consider to be the threshold value of touch. Broman (1945 B) and Moberg (1962) put it at the level where two-thirds and seven-tenths, respectively, of the stimuli were perceived.

Too rigorous a test of touch is often meaningless, since, as von Frey pointed out, the results is dependent on the thickness of the skin. Moreover, the results seem not to be closely related to functional capacity (Moberg, 1962).

Pain

The sharp pin often used in testing the sense of pain provides only a very rough impression of this modality. A more exact measure is obtained with an algesiometer —a method that has not become popular owing to practical difficulties in the performance of the test (Seddon, 1954). There are, however, other more weighty objections to the testing of the sense of pain. When the axons have reached the periphery after a nerve suture hyperalgesia usually appears and may persist. In this hyperalgesic area both touch and pinpricks may elicit the same sensation (Sharpey-Schafer, 1929; Lyons, 1956; Moberg, 1962) and consequently the patient may find difficulty in classing a sensation.

An examination of the sense of pain is included in most follow-up studies. In the lower stages of a scheme for grading sensory recovery, Highet (1943) distinguished between "deep cutaneous pain" and "superficial pain". It is possible that the examination of the sense of pain is of some value in the classification of the results after poor regeneration, but in any case

there is no relationship "between the results of the algesiometric measurements and the functional value of the sensibility" (Moberg, 1962).

To summarize, the tests of the four modalities do not provide a reliable impression of the functional value of the sensibility.

EXAMINATION OF TACTILE GNOSIS

In 1942 it was pointed out by Walshe that the conventional methods of examination were unsatisfactory. Observing subjects examined by these methods and who displayed good regeneration but who were nevertheless unable to perform their work, Bowden (1954) inferred the necessity for distinguishing between "academic" and "functional" recovery. The ordinary sensibility tests reveal only "academic" recovery. It is, however, Moberg (1954, 1958, 1960, 1962) who has emphasized the necessity for a modified view of sensibility. This must be examined in the first place with methods which reveal its functional value. A sensibility of higher functional value is found only when there is tactile gnosis (Moberg). These concepts are therefore practically identical.

Picking-up test

The patient, who is blindfolded, is asked to pick up small objects from a table as fast as possible and place them in a box. Moberg, who introduced this form of test in 1958, found that many patients with normal or slightly elevated touch and pain thresholds, and normal mobility were unable to carry out this test. The same was true of the performance of other everyday tasks requiring precision, such as tying a knot, winding up a clock and doing up a button. The picking-up test has a limited range of application, being reliable only when both contact surfaces are involved by the nerve injury. However, if one surface is unimpaired the test can often be performed surprisingly well (Mannerfelt, 1962).

Coin test

This test, which was introduced by Seddon (unpublished), involves stroking the skin with a smooth-edged and a milled-edged coin. The method may be applied to small as well as large areas of skin. While it provides a fairly good impression of tactile gnosis it is by no means easy to perform, for if the coin is pressed too hard against the skin it may be the "deep sensibility" that is tested (Moberg, 1962).

Digit writing

In this test, wich has long been in use, the subject is required to identify figures traced out on the skin. Moberg (1962) considers that this test has practical shortcomings and that it does not provide information beyond that which may be obtained with other tests of tactile gnosis.

Localization test

It is a familiar experience that in nerve regeneration following a suture it is difficult to localize a tactile stimulus in the field of the nerve (Trotter & Davis, 1909; Boring, 1916). Faulty localization may sometimes even be taken as a sign of nerve regeneration (Hawkins, 1948) and it may persist for many years (Ford &

Woodhall, 1938). Moberg (1962) found that the ability to localize a stimulus was valueless as an indicator of the functional value of sensibility.

Two-point discrimination (2 PD)

Testing of 2 PD, which was introduced by Weber in 1835, involves touching the skin with one or two blunt points of a pair of compasses. The distance between the points is varied and the patient is required to state immediately whether he feels one or two points; it is essential that the points be applied simultaneously and with only a moderate pressure (Ford & Woodhall, 1938). It is important that the direction of the line through the points should be constant, preferably parallel to the finger (Weber). For the transverse direction smaller values are obtained.

As the points are brought closer together it becomes increasingly difficult to discriminate between them, and the two-point stimulus is mistaken for a one-point stimulus, and sometimes vice versa. The threshold value for this test has not been clearly defined; McDougall (1903) placed it at 8 correct answers out of 10 for two-point stimuli; Pontén (1960), Mannerfelt (1962) and Moberg (1962) required 7; Pontén also stipulated that the patient should give at least 7 correct answers out of 10 for the one-point stimuli.

The value of this test has been variously assessed. Recommending it, Head & Sherren (1920) wrote: "By means of the compasses it is possible to obtain information concerning the relative sensibility of parts which react to all the coarser tests". Hutchinson *et al.* (1948) considered it of doubtful value, because they found it difficult to apply the compass points simultaneously and because receptors for both touch and pressure were stimulated. They used the test mainly on the skin of the face, the back of the hand and the abdomen, and the values recorded for normal subjects were widely divergent. Pollock & Davis (1932) wrote: "Two-point discrimination sensation, although of physiologic interest, offers no valuable clinical data". Moberg (1960, 1962), on the other hand, held that there was no better test for evaluating tactile gnosis, although he conceded that the test was not ideal because it required the patient's co-operation.

EXAMINATION OF SUDOMOTOR ACTIVITY

By inspection with a magnifying glass Dieden (1915) and Foerster (1917) noticed that the area supplied by a damaged nerve displays anhidrosis. Using Minor's (1928) iodine starch test Guttmann & List (1928) found a close agreement between anhidrosis and the loss of sensibility. They also noted that the dry area was often surrounded by a hyperhidrotic zone (perilesionary hyperhidrosis). These findings have been confirmed largely by Herz *et al.* (1946), who assessed sudomotor activity by measuring the electrical resistance of the skin.

On the sudomotor activity in nerve regeneration opinions diverge widely. Guttmann & List (1928) considered that the function of the sweat glands returns parallel with the sense of pain. A normal sweat secretion requires that all the sen-

sory modalities be first restored (Guttmann, 1931). Seddon *et al.* (1943) wrote of sweating: "Unfortunately the process is erractic and therefore quite useless for the estimation of rates of regeneration". Klar (1955) considered that sudomotor tests were of inestimable value for assessing the nerve regeneration. Moberg (1962) found that under certain circumstances tests of sudomotor activity were of value after a nerve suture.

A large number of methods for testing sudomotor activity have been described. For clinical use the ninhydrin printing test is particularly suitable; this was developed by Odén & von Hofsten (1954) for criminologic purposes and was introduced and modified for clinical routine work by Moberg (1958). By fixing the prints they may be preserved for a long time.

Another printing test that is of value for clinical work is the iodine-starch method. It is a modification by Randall (1946 A) of Minor's iodine-starch test, further improved by Dole & Thaysen (1953). While the prints keep for only a few months, they are very distinct at the beginning. From a clinical standpoint these two printing methods otherwise give the same results (Moberg, 1958).

REGENERATION OF SENSIBILITY AFTER NERVE SUTURES IN MAN

During and after the First World War several series of nerve sutures performed on war casualties were presented (e. g. Stopford, 1920; Foerster, 1929). All were concerned mainly with the motor component, the results being assessed according to the regeneration of motor function. In the cases in which the sensibility was examined—with needle pricks and with a cotton wool—it was generally found that the sensibility never recovered completely (Sargent & Camb, 1920; Stopford, 1920; Thorburn, 1920; Foerster, 1929).

During the inter-war period nerve injuries lost some of their immediate interest. Bunnell's (1927) pioneer work on digital nerve sutures in the hand attracted little attention. Interest was reawakened with the outbreak of the Second World War. The invalidizing effect of nerve injuries was recognized especially in Great Britain, where a special "Nerve Injuries Committee" was instituted. The need for uniform standards in the evaluation of nerve regeneration was soon realised. A scheme worked out by Highet (1943) gained wide acceptance. This involved a careful grading of both sensory and motor function. The results of this concerted effort were presented in 1954 (Ed. Seddon). While there was no case in which normal sensibility recovered, a number of the subjects showed some return of two-point discrimination.

In the United States, too, analyses have been made of the enormous number of war casualties with nerve injuries. A special organization was set up through which 3656 cases of peripheral nerve injury were followed up. The results were based on the examination of "superficial pain and touch thresholds for the autonomous zones, together with the pain and touch responses to deep pressure" (Ed. Woodhall & Beebe, 1956). The two-point discrimination test was excluded. There was no evidence in the findings that the length of the resected portion of the nerve or the time elapsing between injury and suture were of any significance.

Sunderland (1949) reported a series of 59 nerve sutures with a follow-up period of at least 4 years. Only 2 out of 14 median nerve sutures and one out of 26 ulnar nerve sutures regained some two-point discrimination, which, however, remained defective.

A common feature of all the series of peripheral nerve sutures mentioned is that they were composed only of war casualties, where infection and massive scarring are frequent. The experience gained from these is not directly applicable to peacetime injuries.

Nicholson & Seddon (1957) published the results of a follow-up study of 305 median and ulnar nerve sutures in civil practice. In cases operated on at least 5 years earlier "some return of 2 PD" was obtained in 24.6 and 21.1 per cent of the cases of low median and ulnar sutures, respectively.

In 1958 Larsen & Posch reported their

experience of treatment of 325 nerve injuries of the upper extremities which were followed-up for 1 to 7 years after operation. A two-point discrimination of one centimetre or less was noted after 65 per cent of 142 digital nerve sutures, 72 per cent of 78 low median nerve sutures and 65 per cent of 62 low ulnar nerve sutures.

Stromberg *et al.* (1961) followed up 150 selected nerve sutures situated distal to the middle of the fore-arm. The follow-up period was more than 5 years in 30 cases, 2—5 years in 51 cases, and less than 2 years in the remaining 69. In the case of only 3 adults but of all children below 10 years of age the two-point discrimination returned to normal, or near normal. The sudomotor activity studied by the ninhydrin printing test proved to be of limited value as regards the evalution of the return of function.

In 1962 Sakellarides reported a follow-up study of 172 nerve sutures in the upper extremities of civilians operated upon 2—31 years earlier. Out of 39 cases of primary and 23 of secondary sutures of the median nerve, 2 and 1, respectively, displayed a minimum 2 PD of 3—13 mm (1/8—1/2 inch). The corresponding figures for 40 primary and 30 secondary sutures of the ulnar nerve were 2 and 4.

PRINCIPLES FOR SELECTION OF CASES

The present investigation was intended, as mentioned earlier, as a follow-up study of "ideal" nerve sutures. The following criteria were observed in the selection of the cases.

Clean transection injury

Forty-five of the cases had been cut by glass, 14 by sharp tools and 9 by other sharp objects such as plate metal; one saw injury to a finger which had caused very slight tissue destruction and fibrosis was included with reservation.

In lacerations and contusions there is a risk of interstitial damage to the nerves. At the primary operation this tissue injury may be overlooked by the surgeon (Seddon, 1948) and too small a resection may result. In secondary nerve sutures, however, the extent of the damage is more readily evaluated, and the excision is more likely to be adequate. This gives rise to other difficulties; for since the greatest length of median nerve for which the funicular pattern is constant is 5 mm (Sunderland, 1945), resection of long segments will necessitate the reunion of nerve ends having different funicular patterns. The sprouting axons will then extend more readily into foreign endoneural sheaths. Moreover, more axons will be lost by growing out in the interfunicular spaces, which constitute a significant part of the cross-sectional area (Sunderland & Bradley, 1949, 1950). In clean transections only a very short stretch of the nerve is damaged and the afore-mentioned factors assume less importance.

Level of nerve injury

Only nerve injuries distal to the middle of the forearm were included (not more than 13 cm proximal to the wrist). The great majority of the median and ulnar nerve injuries were at wrist level.

It is known from earlier investigations that there is an association between site of lesion and sensory recovery (Zachary, 1954; Oester & Davis, 1956). The better results in low than high sutures may be due in part to the shorter time required for axons to grow out in more peripherally located sutures but more important is the fact that the further proximally the injury is located the more widely dispersed are the fibres in the cross-section. At the level of the elbow, the sensory and motor fibres of the hand are distributed throughout the cross-section (Sunderland 1949), a fact that favours misdirection of the out-growing fibres.

Complicated injuries

The presence of other simultaneous in-

juries in itself did not constitute a reason for excluding the case. For instance, many injuries at wrist level involved the tendons.

Since one of the objects of the study was to examine the relationship between sensibility and sudomotor activity, it was desirable that there should remain an area of volar skin with intact sensibility. For this reason at first no case of combined complete lesion of the median and ulnar nerves was included. Only a few cases were ruled out on these grounds, however, most of the injuries of this type being rejected for other reasons. On the other hand, 2 cases of complete ulnar lesions combined with partial median injury were included, since the sensibility, at least of the thumbs, was intact throughout.

Two otherwise acceptable cases of total lesion of the median and ulnar nerves with a follow-up period of 11 and 12 years were included as it was desirable to have more cases operated on many years previously. However, they were not as suitable as the other cases for estimation of the sudomotor activity.

Digital nerve lesions were accepted only if both volar nerves to a finger had been divided and sutured. If only one digital nerve had been severed it would not have been certain that the sweat prints had been taken only from the denervated area. Moreover, the evaluation of regeneration on so narrow an area of skin may be complicated by the difficulty in deciding the extent to which any recorded sensibility might be due to the surrounding nerves. While these might, of course, have been blocked, the distances involved in a finger are so short that there was a risk that the anaesthetic would spread and affect the nerve under test.

The prerequisite that both digital nerves of a finger should have been severed and sutured considerably reduced the number of cases that were acceptable for the investigation. This also explains why so many of them had damaged tendons. The mobility, on the other hand, should not be seriously reduced. Restricted mobility in the distal interphalangeal joint of the fingers or the thumb might be accepted provided that the mobility in the other joints of the fingers was not seriously impaired.

Infection

The few cases complicated by infection were rejected.

An infection increases intraneural fibrosis and hence necessitates a more extensive resection.

Interval between injury and suture

The secondary sutures must have been performed within 6 months of the initial injury. Towards the end of the investigation, when it proved that the number of cases would be smaller than was expected, this principle was waived in 7 cases, the 6 months then being exceeded by 8—38 days. These particular cases were accepted because they belong to sparsely represented age groups.

The dependence of the final results on the time factor is evident in practically all follow-up studies. It has been demonstrated experimentally that when nerve sutures in rabbits were delayed by 100 days (Holmes & Young, 1942) or more than 6 months (Berry & Hinsey, 1946; Gutmann, 1942) the success of the operation was prejudiced. A longer delay than

6 months in performing sutures in man has been found to have an unfavourable effect (Foerster, 1929; Zachary & Holmes, 1946; Zachary, 1954). Nevertheless, cases have been reported in which a good functional result has been obtained as long as 10—12 months after the injury (Sunderland, 1950; Nicholson & Seddon, 1957).

The 6-month limit was chosen because in Zachary's comprehensive and carefully followed-up series there was a distinct difference in the results for sutures made within and after the first 6 months of the injury.

Tension in suture line; suture bed

Since tension in the suture line tends to prejudice results, only cases where no such tension was noted were accepted. Because the injuries were clean transections and there was no infection, there was never a large mass of scar tissue. In 2 cases the ulnar nerve had to be transposed at the elbow so that the suture might be placed without tension.

Zachary (1954) found that after resection of more than 5 cm of a median or ulnar nerve not a single case recovered satisfactorily. Sakellarides (1962) observed unfavourable results even for a resection of 2½ cm or so.

It is usually possible to close a large gap between the nerve ends by flexing the joints, but the postoperative stretching of the joints may produce degeneration and intraneural fibrosis (Highet & Sanders, 1943).

Surgeon's experience

The statement that the results of the repair are independent of the surgeon's training (Oester & Davis, 1956) cannot pass unchallenged. There can be few hand surgeons of experience who have not encountered cases in which the median nerve was sutured to a flexor tendon, or a digital nerve to a digital artery. Moreover, it is logical to suppose that an atraumatic technique, operation in a bloodless field and adequate fixation will be of benefit reflected in the final outcome.

Follow-up period

This was chosen on the basis of Zachary's findings (1954), according to which the regeneration takes place mainly during the first 3 years, the next 2 years yielding a small but definite improvement. Sunderland (1949), Nicholson & Seddon (1957) and Stromberg *et al.* (1961) found the same in their series.

Accordingly, a follow-up period of 5 years was taken as the minimum for adult subjects, and 4 years for children below 10 years of age. Both experimental and clinical studies indicate that regeneration takes place more rapidly in young subjects (Gutmann & Guttmann, 1942; Gutmann *et al.*, 1942; Stromberg *et al.*, 1961).

CASE SERIES

CONTROL GROUP

The sudomotor activity was studied in a group of 34 normal subjects—17 women and 17 men, with ages ranging from 12 to 53 years, mostly between 20 and 30 years. On most of the subjects a number of different tests were performed.

The composition of the group with respect to age, and sex was as follows:

	Age group					Total
	12–19	20–29	30–39	40–49	50–53	
Women	3	8	2	3	1	17
Men	3	11	2	1	—	17
Total	6	19	4	4	1	34

NERVE SUTURE GROUP

Nerve sutures fulfilling the requirements specified above—ideal nerve sutures—are by no means common, and to obtain a large enough series it was necessary to take cases from the Sections of Hand Surgery of a number of hospitals:

The General Hospital, Malmö	25
The Sahlgren Hospital, Göteborg	23
Serafimer Hospital, Stockholm	17
St. Göran's Hospital, Stockholm	4
Total	69

An inspection of record cards brought to light a further 11 cases that fulfilled the requirements, but of these 3 had died, 3 were abroad, 3 were living far off, one was a mental patient and one refused to attend follow-up.

Of the 69 patients followed-up 32 had had primary and 39 secondary nerve sutures, 71 altogether. Two cases had had sutures of both median and ulnar nerves. As regards digital nerve sutures, at least 2 of which had been performed on most of the patients, the numbers relate to patients, not to sutures.

The distribution of the series with respect to age, sex and hand injured was as follows:

	Age group (years)							To-
	3-9	10-19	20-29	30-39	40-49	50-59	60-68	tal
Men								
Right hand	9	4	1	2	6	—	—	22
Left hand	6	4	6	1	5	1	1	24
Women								
Right hand	7	3	2	3	—	—	—	15
Left hand	—	5	1	1	—	—	1	8
Total	22	16	10	7	11	1	2	69

Slightly more than one-half of the cases were less than 16 years of age. This predominance of young patients is not typical of an average series of nerve injuries, but is due to the applied principles of selection. In the case of children the great majority of nerve injuries are due to clean

transection, whereas laceration injuries are uncommon. For this reason most of the nerve sutures performed on young persons fulfilled the requirements of selection, but only a fraction of those of the adults did so.

The predominance of right hand involvement up to the age of 10 years is probably due to the type of injury, most of which were caused by the child falling with a bottle in the right hand. After the age of 10 years there was a predominance on left-handed injuries. All but one of the ulnar nerve injuries received by persons over 10 years involved this hand.

The distribution with respect to follow-up period was as follows:

Follow-up period (years)	4	5	6	7	8	9	10	11	12	15	Total
Number of cases	3	17	13	10	4	4	9	6	2	1	69

For two 4- and one 9-year-old boy the follow-up period was a little more than 4 years. For the others it was 5—15 years.

The distribution with respect to the nerves involved was as follows:

Median nerve	Ulnar nerve	Digital nerves
32 sutures	17 sutures	22 cases

Three cases of median nerve sutures were not included because the lesion was at the level of branching in the palm. When several small nerve branches are sutured to a common trunk the suture will always be technically unsatisfactory. In one of the cases included the lesion was so close to the site of branching that the nerve to the third intermetacarpal space had to be sutured separately.

In 4 of the cases assigned to the group of digital nerve sutures it was the superficial terminal branch of the ulnar nerve that was sutured—at or just after the point where the deep motor branch of the ulnar nerve is given off. Apart from a few small motor twigs to the palmaris brevis muscle (Kaplan, 1953) and sometimes a branch to the abductor digiti quinti muscle the superficial branch of the ulnar nerve is entirely sensory, and in this respect resembles the digital nerves rather than the main trunk of the ulnar nerve.

Of the other digital nerve sutures 2 were situated above the division of the common digital nerves into the proper digital nerves, and the others were distal to this point.

EXAMINATION OF SENSIBILITY

TESTED AREAS

The sensibility examinations were restricted to the distal parts of the fingers, that is, the volar aspect of the terminal phalanges, and when required—as in two-point discrimination tests with a large distance between the compass points—to the middle phalanges.

The reasons for this choice of area were the following: (i) the pulp is the most valuable contact area of the finger and has the best tactile gnosis; (ii) the callous skin often found on the palm may considerably complicate a sensibility test; (iii) a test involving the whole area supplied by the median nerve would require several days to perform with the technique in question, and this was not practicable.

FACTORS GOVERNING THE CHOICE OF TEST METHODS

Testing of tactile gnosis

Sensibility tests are time-consuming and fatiguing, and the patient's attention falls off fairly rapidly. It is therefore important to save time and concentrate on the tests that are of most value.

A test should as far as possible reflect the functional value of the sensibility; it should be applicable to all the fingers, and the results should be measurable.

From the account of the various test procedures (p. 10) it is evident that there is, in fact, only one that fulfills these requirements—namely the examination of two-point discrimination. Attention was therefore centered on this test.

While Moberg's *picking-up test* provides an excellent measure of function, its value is limited chiefly to cases of injuries to the median nerve in which the motor function is largely intact. Moreover, the results are difficult to express numerically. The test was performed in appropriate cases of this series.

The *localization test* is attractive from the theoretical aspect since correct localization of a cutaneous stimulus is probably essential for good sensibility. The test was performed consistently but the results were capricious, as Moberg (1962), among others, has also found. When the sensibility was poor greater pressure was required and it is probable that the stimulus was then occasionally perceived by intact nerves some distance away, with the result that an unexpected improvement in localization would be recorded. Here, too, the results are difficult to represent numerically. They were therefore disregarded in the evaluation of the sensibility.

Digit-writing is a sensitive test but it frequently gives unexpected, poor results. This may be due to the patient's

being unaccustomed to figures, or to the manner in which they were formed. No account was taken of these results, therefore, in the evaluation of the sensibility.

In the *five-object test,* which has been used by Moberg (personal communication), the skin is stroked with five different objects; in the present study these were: a gem, a coin, a pencil, a gauze pad and a finger-tip. Metal objects should be at the same temperature as the hand. The test may be carried out on small areas of skin and the results may be graded numerically. This test was used in practically all cases.

Seddon's *coin test* could not be carried out in such a manner as to provide results that were reliable. It is possible that some distortion was due to a slight vibration which was occasionally caused when stroking with the milled coin and which may have been transmitted to normally innervated areas. The test was therefore not used.

Testing of academic recovery

For the examination of "academic recovery" von Frey's hair test involving a graded series of filaments was chosen. The results readily lend themselves to numerical representation. Experience indicated that testing of the sense of pain was of little real value (p. 9) and the same applied to the sense of temperature (p. 8).

Testing of sudomotor activity

The sudomotor activity was examined by means of a slightly modified form of Dole & Thaysen's (1953) method. In this procedure, in which starch-containing paper impregnated with iodine is brought into contact with the skin, active sweat glands are manifested as small blue dots as the water in the sweat reacts with the starch and iodine. The disadvantage of this test is that the prints fade and disappear within a few months. It is, however, distinctly superior to the ninhydrin test.

The fresh prints are sharp and contrasty, and, more important, the sudomotor activity may be followed directly during the trial and may be stimulated as required.

TEST METHODS AND CALCULATION OF THRESHOLD VALUES

Standard techniques were used for Moberg's picking-up test, Seddon's coin test, the localization, digit-writing, 2 PD and the touch tests. The results of the 2 PD and touch tests were evaluated according to new principles and the sweat test was performed by a modification of Dole & Thaysen's method. These last three procedures will be discussed in some detail.

Two-point discrimination test

The patient should be comfortably seated and relaxed, with the hand out- stretched and in a position of rest. The wrist was best held slightly flexed. When it was held in extension there was sometimes a feeling of numbness after a while, with consequent reduction in sensibility. With the finger under test resting in his hand

the examiner fixed the finger-tip by pressing the finger-nail down on the supporting fingers with his thumb-nail. By this means distracting pressure on the volar skin of the finger was avoided. It is important that the subject keeps the finger still, and does not try to press it against the points of the compasses. The compasses were of metal and weighed 52 g; the legs were 11 cm long and the diameter of the blunted tips was 0.5 mm. To enable the subject to get accustomed to the test the examination was started with the point fairly wide apart, but not exceeding 30 mm. The distance was then gradually shortened. Only a slight pressure was exerted—less than would cause paling of the skin. On the other hand, moderate variations in pressure seemed not be of any appreciable importance. The compass points should be applied simultaneously, preferably with the same pressure on each. In the case of skin with regenerated sensibility the patient often stated that one tip felt much more distinctly than the other although there was no appreciable difference in pressure.

For each distance between the points one or more series of tests was performed, each consisting of 10 applications of two points and 10 of one point. It was found necessary to leave 3—4 seconds between applications, since many subjects felt that the stimulus persisted a few seconds after the points had been removed.

It was found best to apply the points to a different area of the pulp each time, and to change fingers after some minutes, since persistent testing on a restricted area often provokes an irritating sensation, which prejudices the results.

The test was considered to be complete when the distance between the points was such that less than one-half of the two-point stimuli were incorrectly identified, in accordance with the applied principles of evaluation (see below). Whereas it is obvious how to evaluate the results obtained with two-point stimuli the interpretation of those for one-point stimuli presents some problems, as is evident from the present tests in which the number of wrong answers ranged from none to practically all. Errors in identifying one-point stimuli were incurred chiefly near the threshold value. Occasionally all responses for two points were correct and all those for one point wrong —that is to say, the subject consistently called "two" irrespective of the number of points applied.

In the case of pure guessing one-half of the answers should be correct, whether one or two points are applied. By subtracting the number of wrong answers for one-point stimuli from the number of correct answers for two-point stimuli the effect of guessing can be largely eliminated. In an ideal "guessing series" of 10 answers of each type the figures $5 - 5 = 0$ would be obtained. This means that in such a series no answer can be considered to be correct.

On this basis it was found most consistent to pursue the same procedure in all situations—that is, always to subtract the number of wrong answers for one-point stimuli from the number of correct answers for two-point stimuli, the same number of one- and two-points tests being performed. The figures so obtained formed the basis for the calculation of the threshold value. It remained to decide where this threshold should lie.

In accordance with the common use of the "median lethal dose" in biologic standardization (Trevan, 1927) the threshold was taken to be that distance between the compass point such that 50 per cent of the two-point stimuli were correctly identified. While the 50 per cent limit is difficult to obtain directly in an investigation, it is readily determined graphically by the probit method (Bliss, 1934; Burn *et al.*, 1950), in which the percentage frequency is replaced by probits, or units of standard deviation. One advantage of this procedure is that relatively few trials are required.

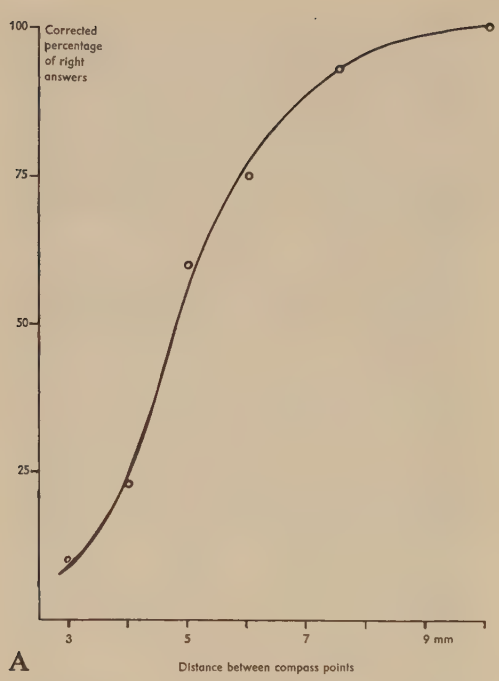
One condition for the application of the probit method is that the values should be normally distributed. In many biologic contexts the distribution of the values themselves is skew but the distribution of their logarithms is normal; the values thus show a log-normal distribution (Bliss, 1934).

To elucidate further the relationship between the percentage of correct answers for two-point stimuli and the distance between the compass points a number of fairly detailed tests were performed. In the threshold zone 4 or 5 inter-point distances were chosen, for each of which the number of trials was doubled. The results were represented graphically as illustrated in Fig. 2. The asymmetric sigmoid curve A shows the relationship between the percentage of correct answers (y-axis) and the inter-point distance (x-axis). In curve B the axis of x carries the logarithmic values of the distance apart of the compass points; this gives a symmetric sigmoid curve. In curve C the y-axis carries probits instead of the percentage frequency and a straight line is obtained. This shows that the original inter-point distances are log-normally distributed because the probit—logarithm relation is recti-linear. The estimation of 50 per cent thresholds is then based on the logarithms of the actual inter-point distances.

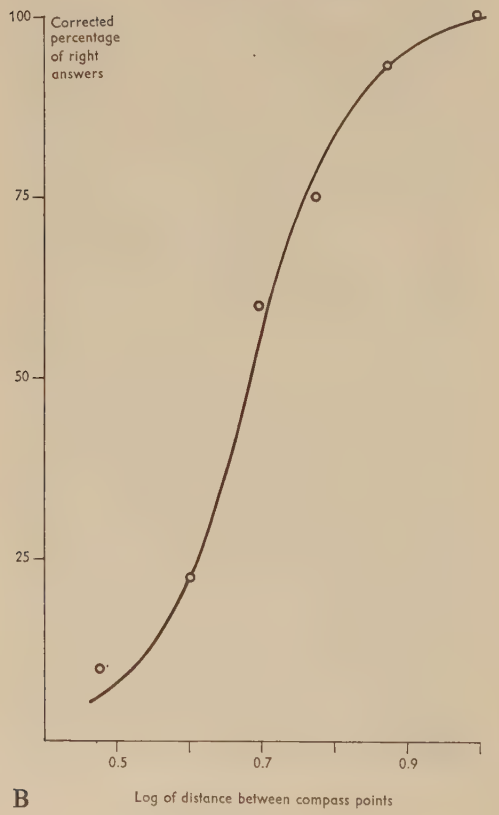
In the determination of two-point discrimination, probit calculations were performed in all cases. The threshold values refer always to the 50 per cent value. It is unfortunate that the number of trials had to be restricted because of the tiring effect of the test, for in several cases a larger series would have increased the reliability of the test. On the other hand, this limitation would hardly have affected the results by more than a millimetre or so, an amount that would have had a negligible influence on the end results.

The upper limit for the two-point discrimination test was set at 30 mm—that is, approximately 10 times the normal value (p. 25). If the points can barely be distinguished when 30 mm apart the sensibility must be very poor and extension of the test beyond this limit would be to no purpose. With greater distances there is also the difficulty that one point may be placed on skin the tactile gnosis of which is relatively poor even in the normal subject. A more important factor, however, is the increased difficulty of making simultaneous two-point contact with the skin for greater distances. Even for quite a small difference between the moments of contact there is a marked improvement in the ability to discriminate between two points.

Normal values.—In the case of normally innervated skin it was exceptional for one point to be perceived as two. The



A



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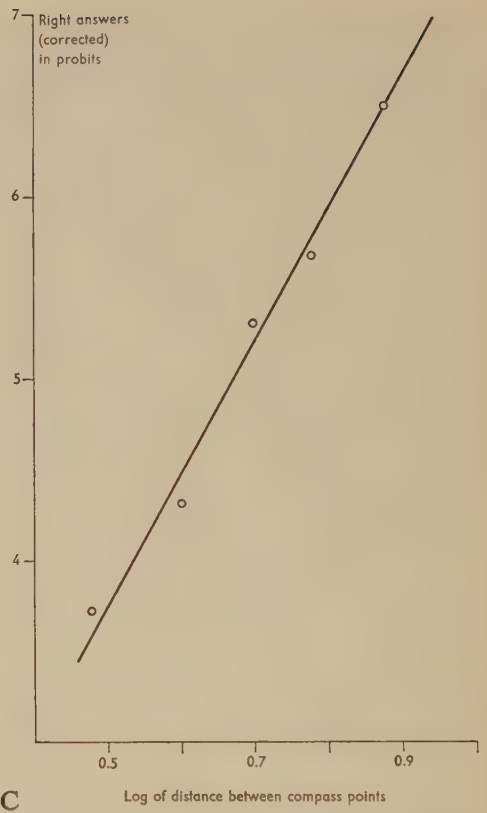


C

Fig. 2 Relationship between number of correct answers in a 2 PD test and the distance between the compass points.

A, Abscissa: distance between compass points; ordinate: percentage of correct answers. Asymmetric sigmoid curve.

B, Abscissa: logarithm of distance between compass points; ordinate: as in A. Symmetric sigmoid curve.

C, Abscissa: as in B; ordinate: frequency expressed in probits.

zone of uncertainty was narrow—that is to say, only a small reduction in the distance between the points (1—2 mm) was required for a subject who had correctly recognized all, or nearly all, two-point stimuli to identify them as one-point stimuli. There was one case in which a reduction of from 2 to 1 ½ mm was enough to cause such a reversal.

Absolute 2 PD values were used when determining the normal threshold, there being no advantage in using logarithms or probits. The threshold for 2 PD was taken as the value at which the subject began to identify the objects incorrectly.

Moreover, in the calculations no account was taken of the magnitude of the normal values.

The normal values differed slightly from one subject to another. In the present series some children of 8—12 years were sometimes able to discriminate between points only 2 mm apart; in general, however, the minimum was 3—4 mm. In 5 cases it was 5 mm and in one case 6 mm—values that relate to the two ulnar fingers.

TABLE I. *Difference between 2 PD values on two occasions of testing.*

Case no.	2 PD value			
	Digit	First test	Second test	Difference
10	II R*	4	5	+1
	U	5	5	—
13	I R	7	9	+2
	U	9	7	−2
25	II R	29	30	+1
	U	25	26	+1
41	V R	25	22	−3
	U	19	17	−2
53	V R	2	2	—
	U	2	2	—
54	V R	4	5	+1
	U	5	5	—
55	I R	3	3	—
	U	3	3	—
56	IV R	8	5	−3
	U	7	5	−2
62	IV R	17	9	−8
	U	17	12	−5
67	I R	14	13	−1
	U	14	12	−2

* R, radial side; U, ulnar side.

The reliability of the technique and method of calculation is evidenced by the close agreement between the 2 PD values recorded at intervals of 6—12 months for out of 10 randomly selected cases of nerve sutures (Table I). The deviation in case 62 is difficult to explain.

In the clinical application of the two-point discrimination test an approximate determination of the threshold value will usually suffice, a deviation of a few millimetres in either direction being of negligible importance. This schematic form of test takes only 5—10 minutes.

von Frey's hair test

This test was performed with 5 nylon threads of different diameters mounted on a bicycle spoke and calibrated against a balance so as to exert a pressure of 0.3, 0.5, 1.0, 1.5 and 2.5 g when they just bent. The error due to the variation in the pressure as the thread bent was relatively small for minor deformations.

The maximum pressure used was 2.5 g—that is, about 10 times the normal value. There appeared to be no reason to use a smaller pressure than 0.3 g, for when the touch is light the results are too much affected by the thickness of the skin.

The limiting value was taken as that at which 50 per cent of the stimuli were perceived. This value was calculated by the probit method.

Test of sudomotor activity

The sweat secretion was measured quantitatively by comparing the number of simultaneously active glands on equal symmetrical areas of each hand (Randall,

1946 A). Dole & Thaysen's iodine-starch printing method proved to be the most suitable for this purpose. Certain problems were encountered, however. The same starch-containing paper was used as is recommended by the originators of the technique. The paper frequently darkened on iodizing, so that the sweat dots were difficult to distinguish. Two reasons for this were detected; the paper absorbed more water in humid weather, and the water vapour from the gas flame used as a source of heat sometimes penetrated into the dish in which the iodizing was performed.

To avoid these difficulties a chamber was designed in which the paper could first be dried and then iodized (Fig. 3).

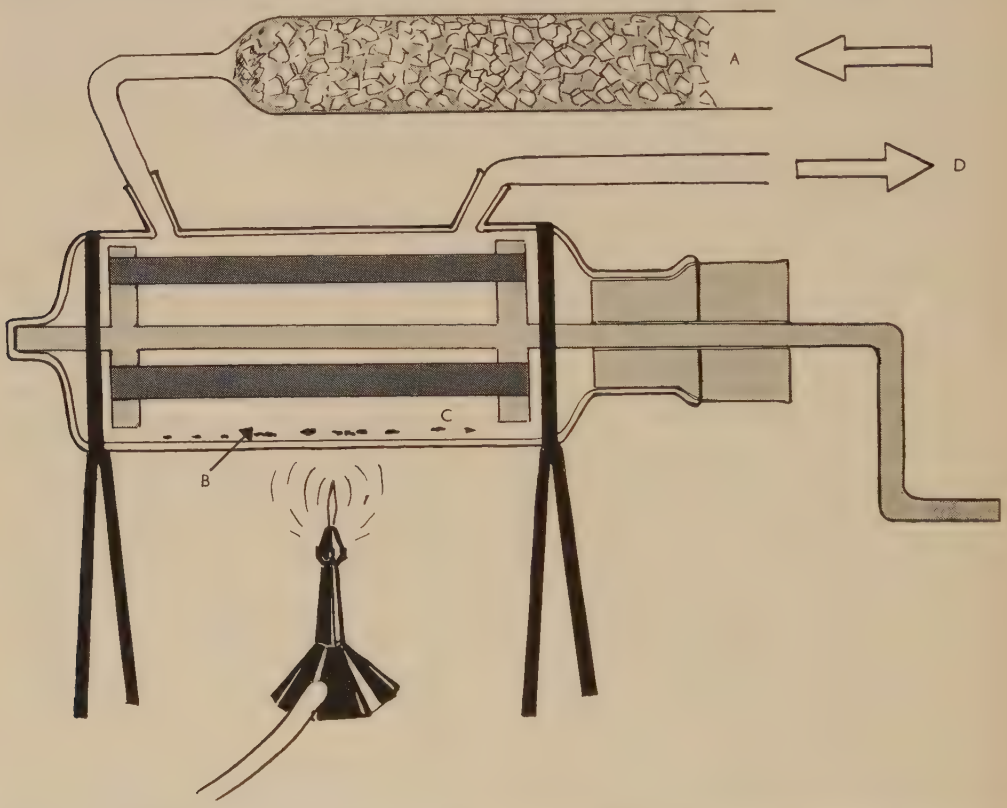


Fig. 3 Glass chamber for drying and iodizing the paper strips. A, water-absorbing silica gel; B, iodine crystals; C, paper strips; D, to water pump.

This chamber consists of a glass cylinder with an axial shaft and two glass discs. The paper strips to be iodized are stretched between the discs. As the shaft is turned the strips act as a fan. The chamber is heated with a gas flame and ventilated with air that has been dried by passage through silica gel. After 5—8 minutes of drying a few crystals of iodine are inserted in the chamber; these rapidly vaporize and the iodine is deposited on the paper, which turns a light yellowish-brown. For each trial freshly prepared paper is used.

Though, on exposure to the air, much of the iodine evaporates in the course of 20—30 minutes and the dots developed by the water in the sweat may fade slightly, they retain their dark blue colour for weeks and may still be distinguishable after some months.

The printing technique also presented problems. To reduce the random error it was desirable to have a series of simultaneous prints from symmetrical areas of the pulps of corresponding fingers.

The final design of the apparatus for taking the prints is shown in Fig. 4.

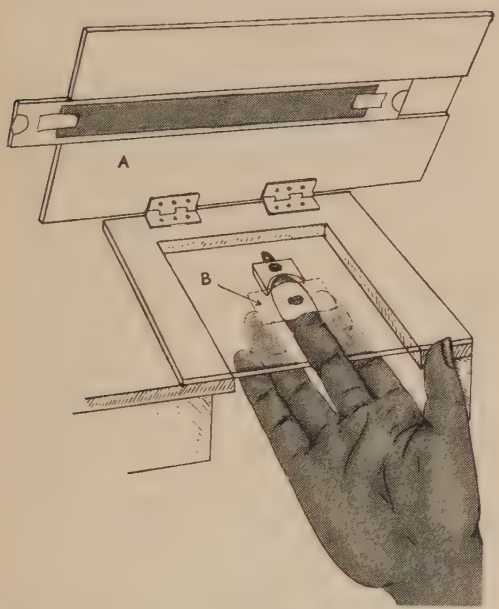


Fig. 4 Apparatus for taking sweat prints. A, iodized paper strip; B, adhesive tape with punched hole.

One pair of fingers is tested at a time. The skin is covered with tape in which a hole, 5 mm in diameter, is punched over the centre of the pulp. On the under surface of a lid-like device the freshly iodized adjustable paper strip is mounted. When the lid is pressed down the paper comes into contact with the circular exposed area of the finger, and the sweat droplets are registered as blue dots (Fig. 5).

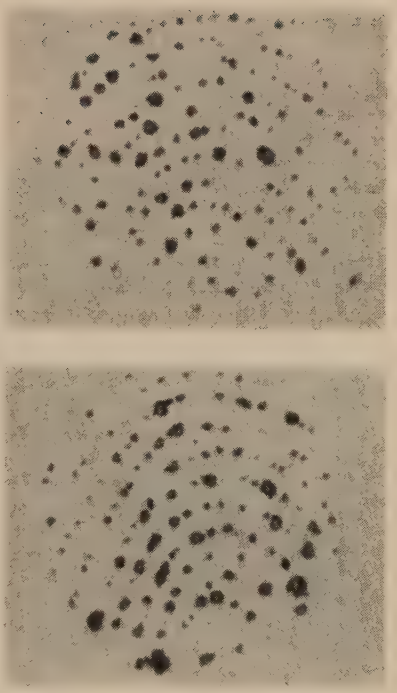


Fig. 5 Normal prints from a pair of middle fingers.

As a rule prints were taken every 10 or 15 seconds, and the paper was kept in contact with the skin for 2 or 5 seconds. In the case of hyperhidrosis, prints were taken more frequently and the exposure was limited to one second. In most cases a series of 16 prints was taken, the first of which was rejected. As soon as possible thereafter, the dots were counted under a microscope at a magnification of 40. The values so obtained were recorded graphically. The consistency of the curves for the normal corresponding fingers is striking (Fig. 6).

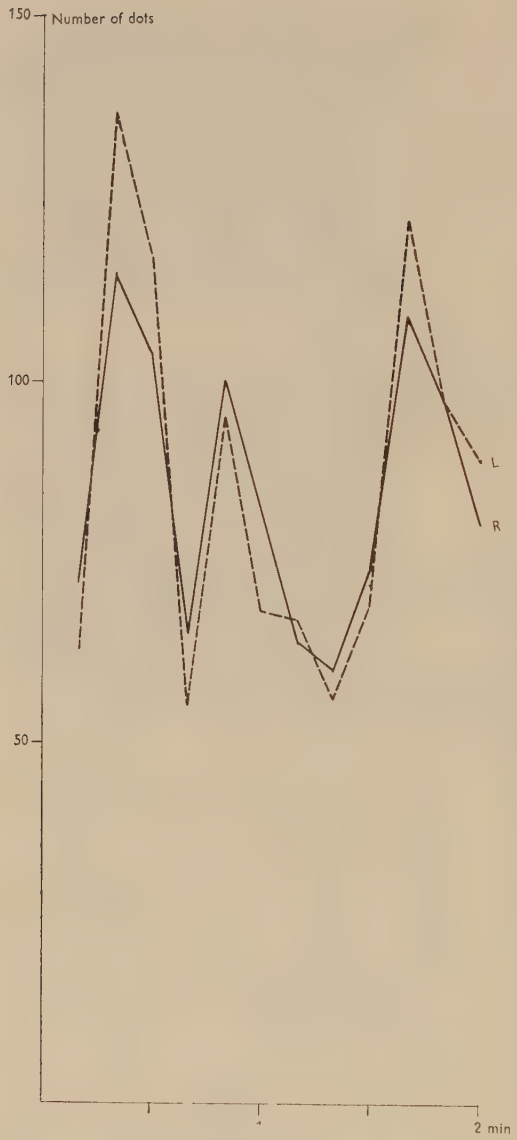


Fig. 6 Relationship between the number of active sweat glands for a pair of normal middle fingers.

STUDIES ON PALMAR SWEATING

Before examining the sudomotor activity after nerve sutures certain methodologic studies were performed.

STIMULATION OF PALMAR SWEATING

An average of 25 active glands per print on healthy skin was decided upon as an acceptable lower limit of sudomotor activity. To obtain enough active glands it was frequently necessary to stimulate palmar sweating.

It is known that palmar sweating is effectively stimulated by mental stress (Jürgensen, 1924; Minor, 1928) or interruption of the circulation in an arm by means of a blood pressure cuff (Kuno, 1956). An increase in the number of secreting glands is followed by intensification of activity of the individual gland (Randall, 1946 B; Randall & McClure, 1949). It was found that the most simple, and often the most effective, means of stimulating sweat in the adult was to discuss sensitive subjects with the patient during the course of the experiment. In the case of children mental arithmetic was a useful aid.

Some patients were resistant to all attempts at mental stimulation. As a rule the older the patient the more difficult it was to provoke sweating by this means. Muscular exercise was tried occasionally but this was difficult to perform during the experiment and the effect was transient. The method of interrupting the circulation by means of a blood pressure cuff at 300 mm Hg was then resorted to, and this method often produced the desired result. The effect of ischaemia on the sudomotor activity is discussed below.

In a few cases none of the above measures provoked intense enough sweating for quantitative study.

ERROR OF THE METHOD

In the studies on normal subjects it was often noted that sweat secretion was not the same on symmetrical areas of the pulps of the two hands but this may have been due to the inaccuracies in the method. It has been shown by Dole & Thaysen (1953) that the intensity with which the paper is iodized is of no significance. The strips used in the present study were, moreover, iodized simultaneously. On the other hand, certain technical details called for closer examination.

Distribution of active sweat glands on the pulp

Though every attempt was made to take the prints at as nearly symmetrical areas of the pulps as possible small deviations were difficult to avoid. To examine this problem the following tests were per-

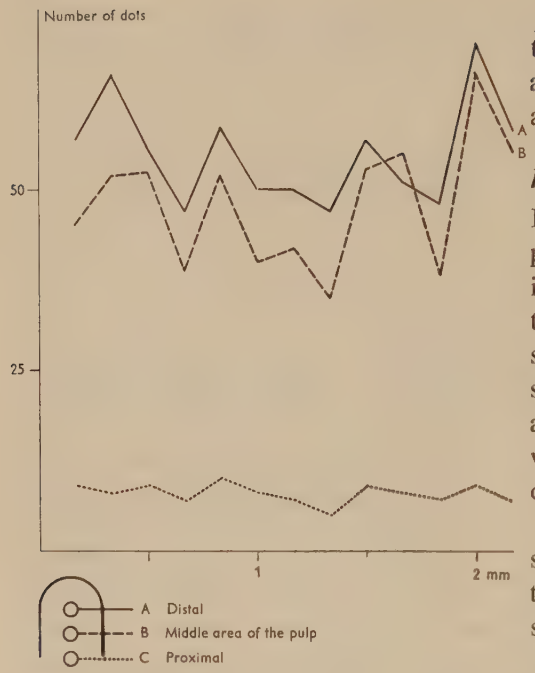


Fig. 7 Relationship between number of active sweat glands in distal, middle and proximal areas of the pulp. The number is very much lower near the flexor crease.

formed 14 times with minor differences on a group of 8 subjects. Simultaneous prints were taken from 2 or 3 different areas on the volar aspect of a terminal phalanx. The curves in Fig. 7 for the distal and middle areas of a middle finger are practically identical, while the curve for the proximal surface lies considerably lower. The findings are in complete agreement with those of earlier workers (Minor, 1928; Kuno, 1956), the sweat glands registered being more numerous on the projecting parts of the hand, the finger and the thenar and hypothenar eminences and fewer near the creases. In the areas distal to the actual creases, however, the sweat secretion was strikingly uniform.

It would seem from this experiment that it is not necessary for the prints of a pair to be taken on exactly symmetrical areas of the pulps.

Pressure applied to the paper strips

If the number of dots depends on the pressure applied to the strips inequalities in this would give rise to differences between the two sides. The curves in Fig. 8 show the results obtained by applying a strong pressure on one index finger and a light pressure on the other, and conversely, several times in succession, a pair of prints being taken each time.

The number of dots for strong pressure was slightly greater, but in all 8 trials the difference was insignificant in spite of the large variation in pressure.

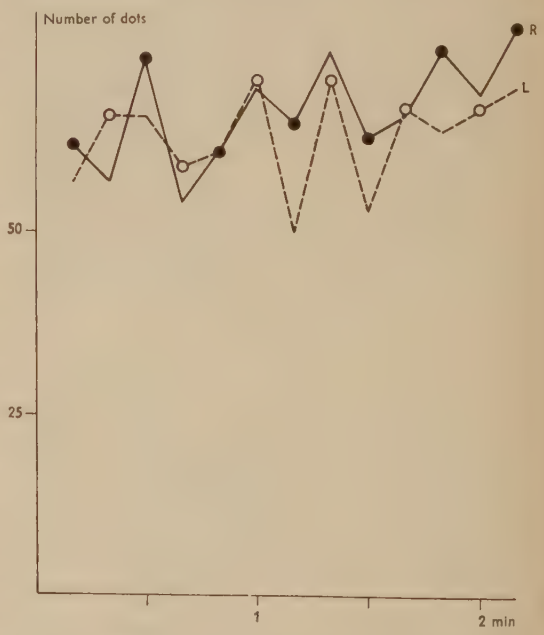


Fig. 8 Effect of printing pressure applied to the finger on the number of registered sweat glands. Filled and open circles denote marked pressure on the right and left forefinger, respectively.

Effect of local ischaemia

At the beginning of this investigation it was the practice to attach the finger to the support by means of the perforated strip of tape. Even a slight displacement of the finger might then result in pressure of the tape on the finger so that the pulp became ischaemic. To ascertain the effect of such local ischaemia 10 tests similar to those illustrated in Fig. 9 were performed.

The first two pairs of prints show the initial position. As the pulp of the right index finger was compressed with the tape strip (left arrow), there was an immediate reduction in the number of active glands. As the pressure on the right index finger was released and transferred to the left finger (right arrow), the number of active glands on the right finger recovered immediately and that on the left side fell. In all 10 tests the changes were consistent. It was evident that local ischaemia considerably affected the results, and the technique of securing the fingers with tape was therefore discontinued.

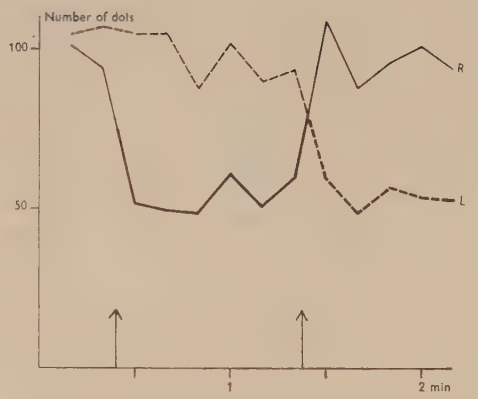


Fig. 9 Local pressure reduces the number of active sweat glands. Left arrow, pressure applied to right forefinger; right arrow, removal of pressure from right to left forefinger.

NATURAL VARIATIONS IN RIGHT-LEFT SYMMETRY

A study was made of the relationship between the number of active sweat glands on corresponding finger areas of the right and left hands with the aforementioned precautions, the tests were performed on 17 subjects, 10 men and 7 women, with ages ranging from 12 to 45 years; altogether 50 pairs of fingers were examined. A series of prints was taken and an average of slightly more than 1000 dots per finger was counted.

Table II shows the quotient of the number of dots on the right hand by that on the left (sweating index right/left). In 9 of the 50 pairs of fingers the difference exceeded 20 per cent, the range being 0.69—1.38. The quotient of the left by the right side gives the range expressed as the reciprocals of the former values, namely 0.72—1.45. The variations of the sweat index in the normal group thus lay within the limits 0.69 and 1.45, or between $\frac{2}{3}$ and $\frac{3}{2}$. In none of the cases in which most or all of the fingers were examined was there a general hypo- or hyperhidrosis—with the possible exception of case 5.

The results are in agreement with those of other workers; Herrmann *et al.* (1952) found "natural asymmetry" in 20 per cent of the skin areas tested; Knudsen (1961) noted roughly the same tendency, with a difference of more than 20 per cent in 6 out of 25 subjects.

TABLE II. *Relationship between the number of active sweat glands on the corresponding digits of the right and left hands (sweat index R/L).*

Case no.	Digit	Sweat index R/L	Case no.	Digit	Sweat index R/L	Case no.	Digit	Sweat index R/L
1	II	0.89	8	II	1.05	14	I	1.25
	III	0.99		III	0.99		II	1.01
				IV	0.80		III	1.14
2	III	1.13		V	1.04		IV	0.69
							V	0.69
3	III	0.96	9	III	0.97			
	IV	1.07				15	II	1.11
			10	I	1.34		III	1.15
4	II	0.95		II	0.85		IV	1.00
	III	1.09		III	0.89		V	0.98
				IV	1.01			
5	I	1.11		V	0.99	16	I	0.88
	II	1.10					II	0.97
	III	1.02	11	II	0.99		III	0.71
	IV	1.22					IV	0.83
			12	III	0.79		V	1.15
6	II	0.98						
	III	0.90	13	II	1.11	17	I	1.00
				III	1.16		II	1.22
7	II	0.92					III	0.96
	III	0.92					IV	0.86
	IV	1.00					V	1.14
	V	1.38						

EFFECT OF TRAUMA AND INFECTION

It was evident at an early stage of the investigation that trauma may affect the sudomotor activity outside the immediate area involved by the trauma.

In order to examine this possibility the sudomotor function was studied in 8 subjects—2 with a fresh lesion and 6 with closed injuries; in all cases the finger pulps and their innervation were intact. Several of the cases were followed from one to 14 weeks. Fig. 10 shows the sweating curves less than 24 hours after an avulsion fracture of the terminal phalanx on the right ring finger. On an average only one third as many sweat glands secreted on the damaged finger as on the healthy one. The prints in Fig. 11 were taken 3 months after a still unhealed injury to the ligaments of the middle joint of the left third digit. The sudomotor activity was reduced also in the left fourth and fifth digits, but not in the index.

In all cases hypohidrosis was noted in the injured finger, and in some cases it extended to the adjacent fingers (Fig. 11). When the injury had healed the sudomotor activity recovered gradually.

The sudomotor activity was examined

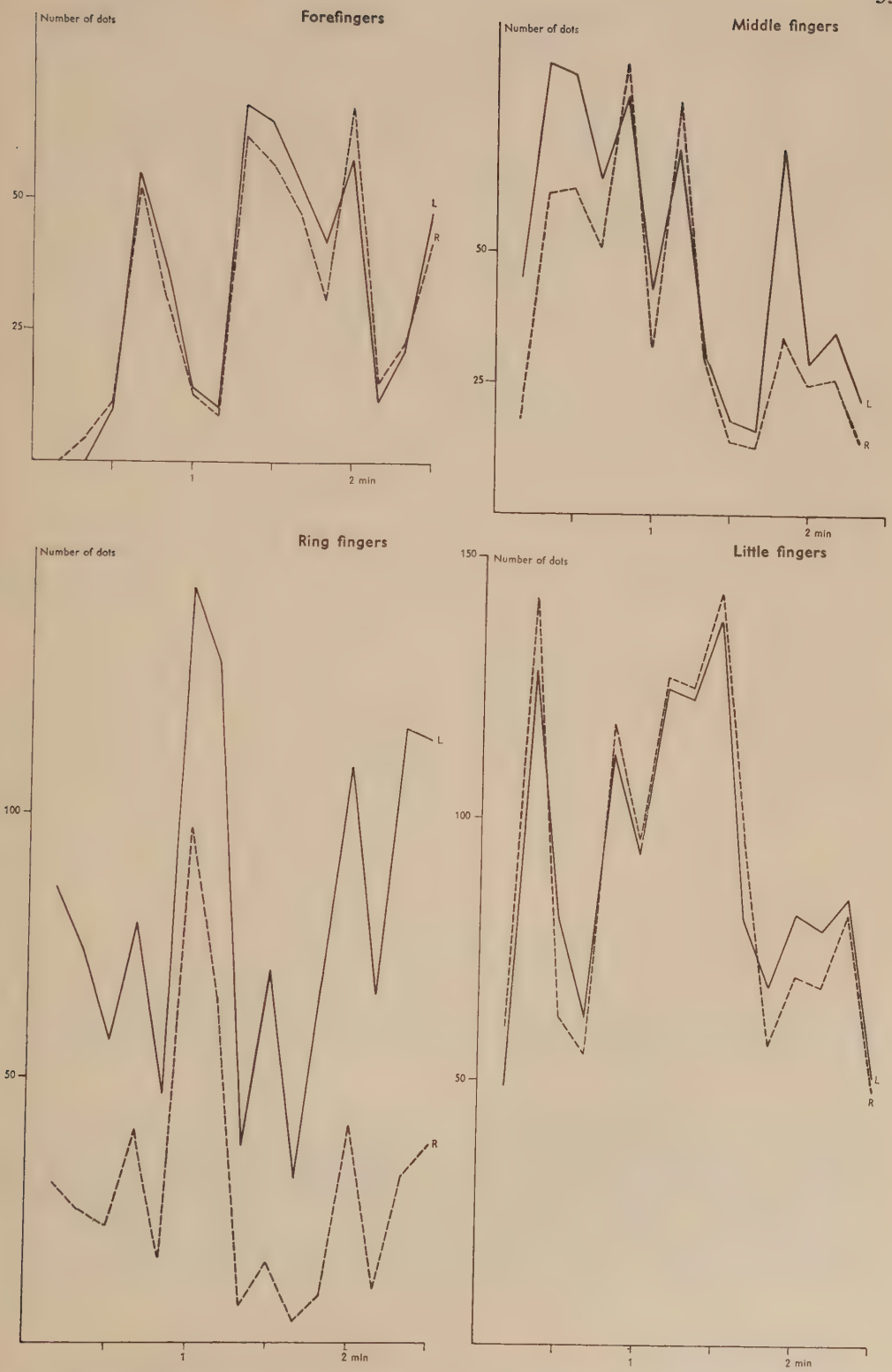


Fig. 10 Effect of one-day-old avulsion fracture of right ring finger on the number of active sweat glands registered on all four fingers. The affected finger displayed marked hypohidrosis.

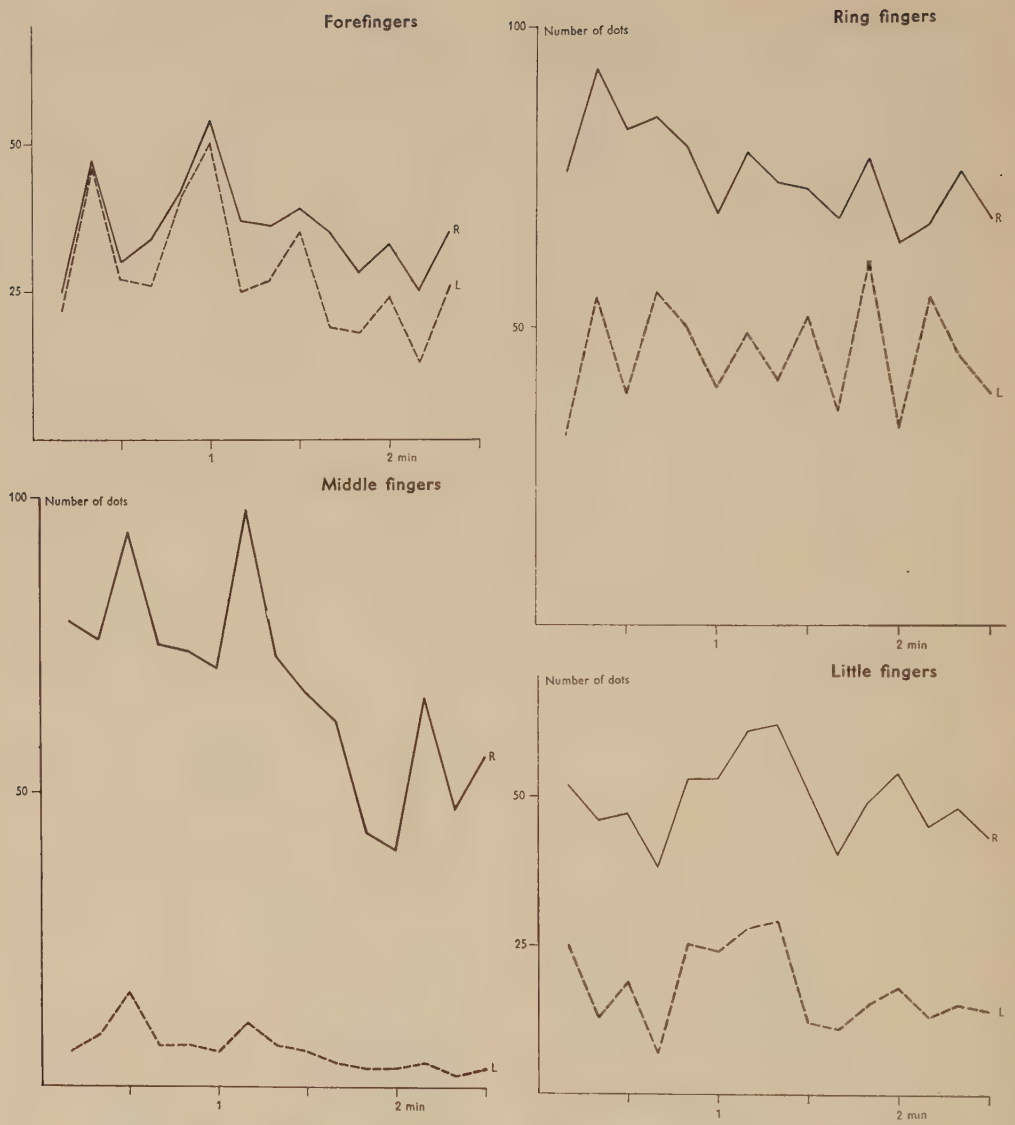


Fig. 11 Effect on sweat secretion of three-month-old injury to ligaments of left middle finger. Pronounced hypohidrosis was noted on the damaged finger, and to a much less extent on the ring and little fingers.

in 16 cases of finger infection. Fig. 12 relates to a case of abscess on the dorsal aspect of the proximal interphalangeal joint of the right little finger. Only a few sweat glands were active on the infected finger, the ring and middle fingers displayed a lesser degree of hypohidrosis, and the index was normal. A paronychia greatly reduced the sweat gland activity in the affected left middle finger (Fig. 13); in the adjacent digits the number of active glands was practically nor-

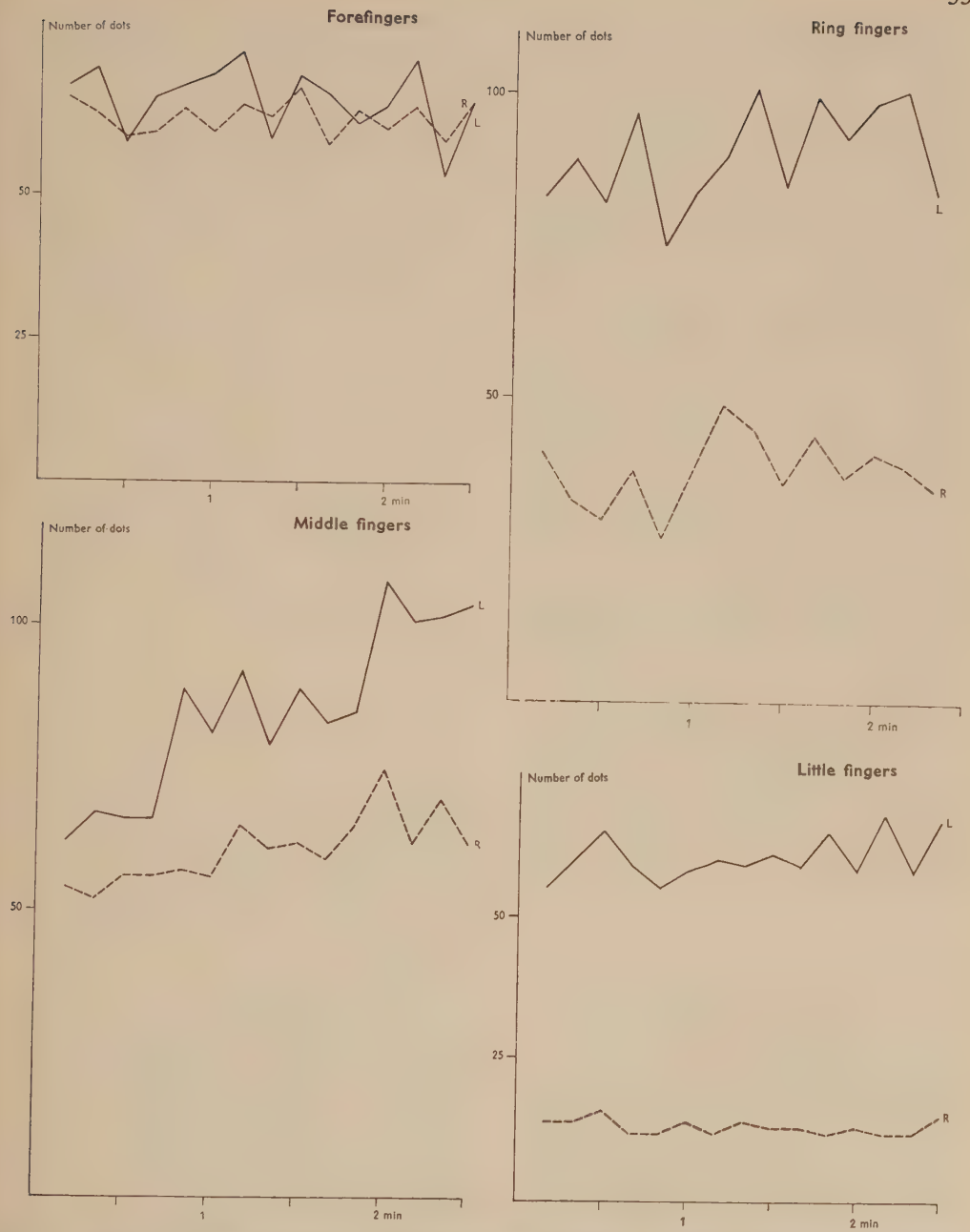
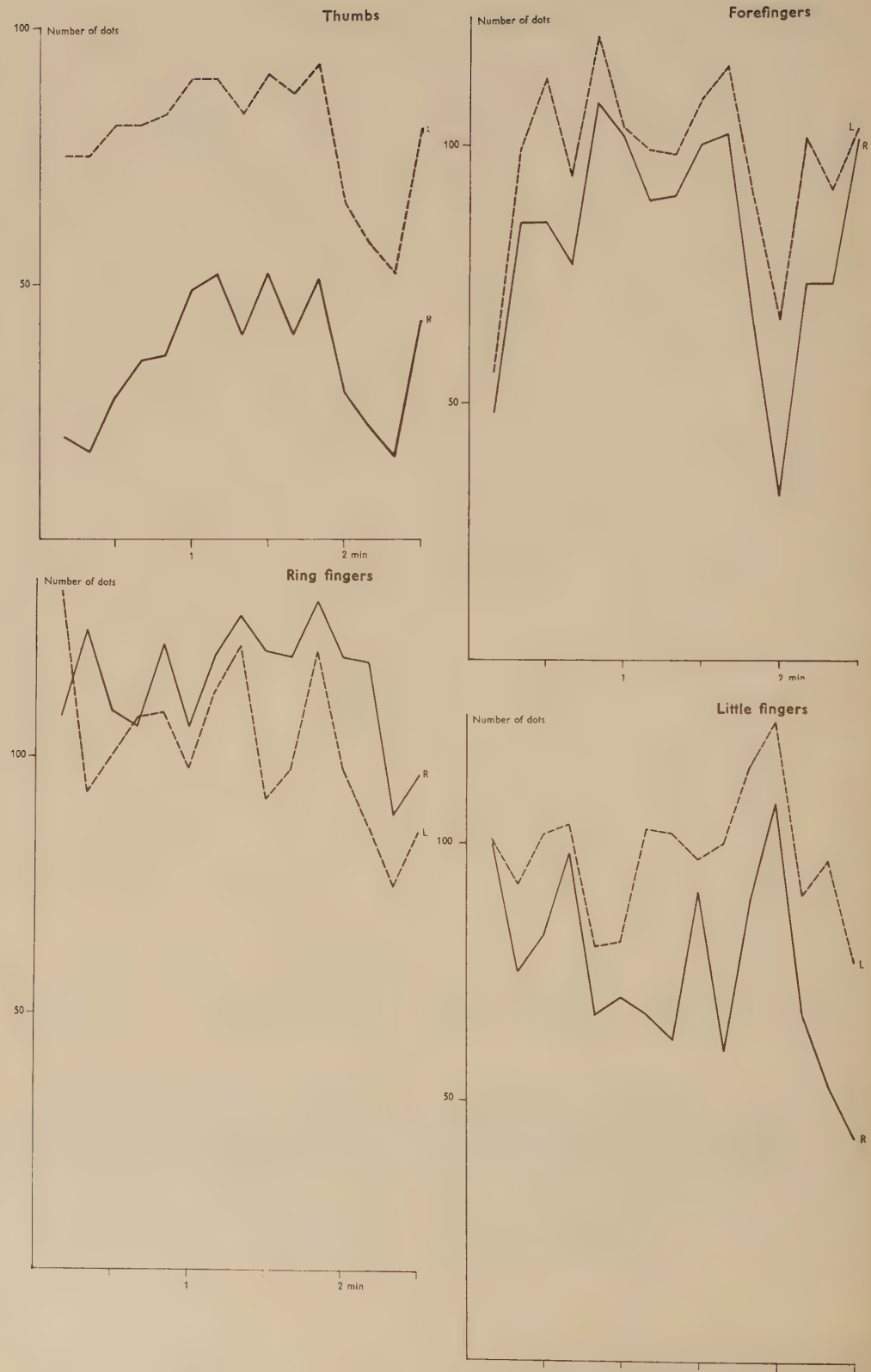


Fig. 12 Effect on sweat secretion of abscess on dorsal aspect of right little finger. Pronounced hypohidrosis was noted on the damaged finger, less on the ring finger and still less on the middle finger.


Thumbs
Number of dots
100
50
L
R
1
2 min
Forefingers
Number of dots
100
50
L
R
1
2 min
Ring fingers
Number of dots
100
50
R
L
1
2 min
Little fingers
Number of dots
100
50
L
R

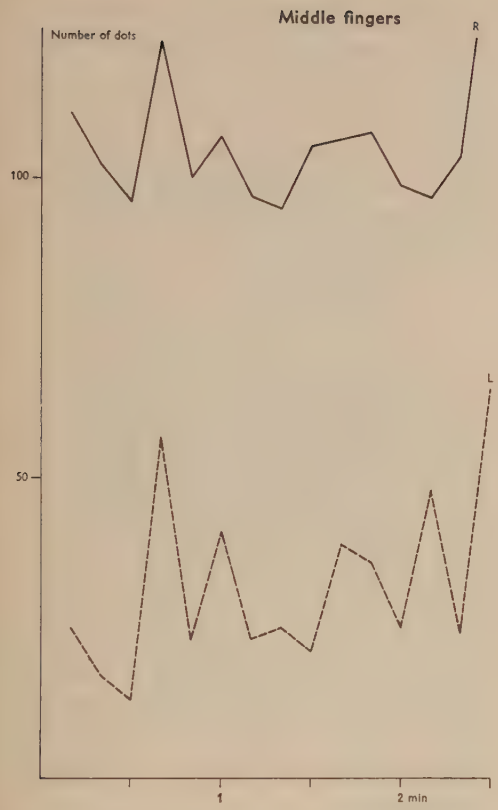


Fig. 13 Effect on sweat secretion of acute paronychia on the left middle finger; pronounced hypohidrosis on the affected finger, normal number of active glands on adjacent fingers, hyperhidrosis on thumb and little finger.

mal; the thumb and little finger, however, displayed a greater number of active glands.

This impaired vegetative function may be due to blocking of the nerve fibres owing to tissue pressure set up by the inflammation or by oedema of the nerves. By applying pressure to the arm the larger fibres are blocked before the smaller ones (Fabritius, 1912; Gasser & Erlanger, 1929; Bishop, 1960), and consequently the larger sensitive nerve fibres would be involved before the smaller autonomous fibres. In the cases with pronounced oedema, no deterioration in two-point discrimination was noted. The vegetative dysfunction must therefore have some other explanation. Haldbo (1942) suggests that there may be paralysis of the nerve cells in the vegetative system.

Hypohidrosis following a trauma or an infection thus cannot be considered as evidence of incomplete nerve lesion or regeneration. On the other hand, in neither trauma nor infection was there a total extinction of sweat secretion, as is the case after complete nerve lesion.

SUDOMOTOR ACTIVITY AND ISCHAEMIA

It has been shown that within the area of ischaemia produced by local pressure the number of sweat glands active at one time is momentarily reduced (p.31). What will be the effect of interrupting the circulation at the base of the finger or at the level of the upper arm? In 10 trials on 7 normal subjects the circulation was interrupted in a finger by pulling a length of rubber tubing tight around its base. The tubing was loosened after 2—5 minutes. On 8 fingers this constriction had no effect, but 2 fingers of one subject showed a progressively slower rate of secretion than the control finger of the other hand. While it is possible that the rubber tubing in these two trials exerted a particularly strong pressure on the digital nerves, this decrease in activity could not be reproduced on other subjects even when the tubing was pulled very tightly.

In 12 trials on 9 normal subjects the

circulation was interrupted by inflating a blood pressure cuff round the upper arm to 300 mm Hg for 2—7½ minutes. In no case was there any noticeable difference in sudomotor activity between the tested and control fingers. Nor was there any difference when the blood was first removed from the extremity by wrapping it with an Esmarch bandage.

These findings are in accordance with the experience of other writers (Dieden, 1915; Randall *et al.*, 1948; Kuno, 1956; Collins *et al.*, 1959). A short period of interruption of the circulation—5—15 minutes—does not depress the sudomotor activity in the arm in which no blood is flowing.

ACTIVITY OF INDIVIDUAL SWEAT GLANDS

A study, not directly connected with the rest of the investigation, was made of the sudomotor activity of individual glands by taking prints every 6 seconds on 2 normal subjects and every 15 seconds on the third. In one trial 25 prints were taken during moderate secretion (Fig. 14), in another trial 20 prints were taken during fairly intense secretion (Fig. 15), and in the third, 15 prints during slightly more intense secretion. Each dot was identified.

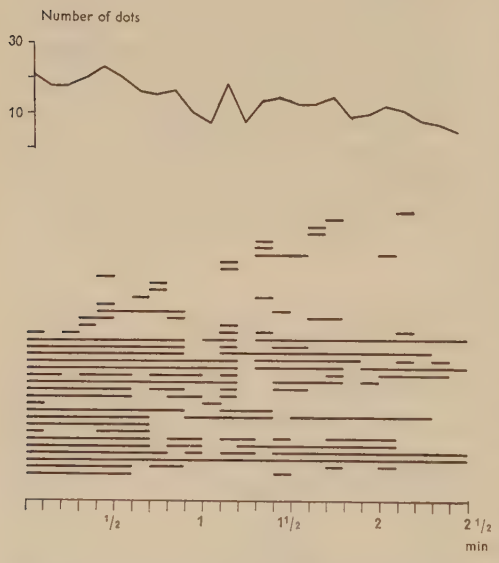


Fig. 14 Prints from right middle finger of a 42-year-old woman with moderate sweat secretion. The curve shows the variation in the number of glands active at one time; the horizontal lines indicate the periods during which the individual glands were secreting. Prints were taken every 6 seconds.

In the first trial not more than 23 glands discharged simultaneously out of 38 observed for 2½ minutes. Only one gland secreted continuously; 12 glands were recorded only once. Only a few glands showed any tendency to regularity of secretion.

In the second trial about one-half of the glands discharged continuously and the other half irregularly. One gland was recorded only once. At no time were more than 58 out of 61 active glands discharging simultaneously.

In the third trial 49 out of 68 glands observed discharged continuously, a maximum of 66 glands at one time.

These findings do not rule out the possibility of a constant fluctuation in the secretory activity of an individual gland such as Takahara (1934) observed. A fluctuation of this type is difficult to demonstrate by the method used unless each period is marked by a complete and sufficiently long interruption of secretion.

The 3 trials provide no evidence that

Fig. 15 Prints from the right thumb of a 45-year-old man with fairly intense sweat secretion. (For explanation see caption Fig. 14).

there are three main physiologic types of glands as Lobitz & Osterberg (1947) have reported. The activity of glands would seem to be dependent largely on the intensity of stimulation.

MEDIAN NERVE SUTURES

The findings relating to the 32 sutures of the median nerve are presented in Table III (p. 42—43).

Subjective assessment

Eleven patients, aged 4—18 years at operation, considered that they had completely recovered (—). They were seldom if ever reminded of the injury. In 6 of these cases, however, there was a distinct but slight change in the quality of the sensibility as the examiner's finger-tip passed into the median territory. The other 5 subjects detected no such change.

Seven patients, aged 4—43 years, reported mild symptoms (+). These include the 2 cases with combined damage to the median and ulnar nerves. It is possible that their symptoms were due to motor rather than to sensory defects. One subject had been ambidextrous prior to the accident but subsequently used only the left hand and became left-handed. In other cases of injury to the dominant hand there was no noticeable transference of dexterity to the normal hand.

Eight patients, aged 9—34 years, complanined of discomfort which might be termed moderate (++). They were constantly reminded of the injury.

Six patients, aged 21—57 ,were assigned to the "severe symptoms" group (+++). They had little if any use of their three fingers supplied by the median nerve, none of which bore any wearing marks. The three oldest patients at operation were among these 6 subjects.

Two-point discrimination

As a rule results of the 2 PD test were available for both radial and ulnar surfaces of the first 3 digits. It is difficult, however, to derive a general impression from so many numerical data relating to a single patient. While this might be simplified by taking the mean of all 6 2 PD values, it was preferred to take the mean for the radial and ulnar aspects of the index finger as representative of the whole median field. This alternative was chosen because it is only on the index fingers that the volar aspect is always supplied by the median nerve.

This restriction was usually unnecessary since there was no difficulty in delimiting the distribution of the median nerve except in those cases where sensibility had returned to normal, or nearly so. It is then impossible to establish a definite boundary either subjectively or objectively without blocking the neighbouring nerves (Highet, 1942). This was considered impracticable except in respect of the radial nerve branches to the thumb. In only a few cases in which there might be doubt about the limits were these nerves not blocked, but since blocking was not used consistently is was considered better to employ only the values for the index fingers. As a rule the 2 PD

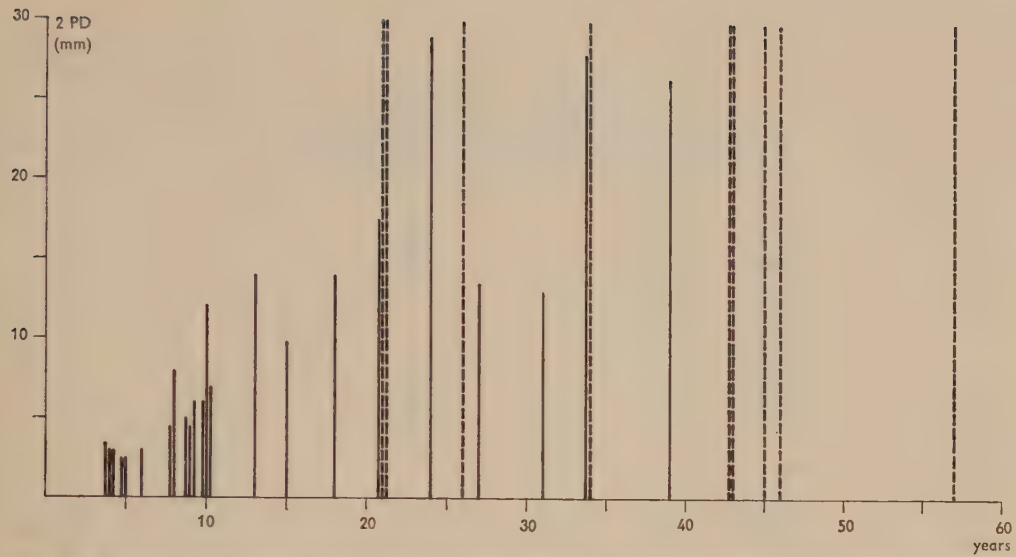


Fig. 16 Median nerve sutures. Relationship between mean 2 PD for index fingers (at follow-up) and age of subject (at suture). Each line represents one subject. The broken lines relate to 2 PD values exceeding 30 mm.

values were the same for the radial and ulnar aspects of these fingers. In 4 cases the difference exceeded 2 mm (6, 7, 7 and 4 mm).

To what extent are the results affected by this restriction? What is the range of variation between the various fingers of a particular subject? The values for the middle fingers (Table III) were, with a few negligible exceptions, practically identical with those for the index fingers, so that it is immaterial whether the middle finger values are disregarded. The same is largely true of the values for the thumbs. Exceptions are 6 cases in which the thumb values were considerably lower, that is to say the discrimination was better than for the index fingers. In no case did the values for the thumb exceed those for the index finger by more than one millimetre. It may be noted that in all cases where the two-point discrimination was better for the thumb no change in sensibility was noted on blocking the branches of the radial nerve.

It is evident from Fig. 16 that there is a close association between the age at operation and the 2 PD value. For all 6 patients below 7 years of age the 2 PD values were only 2—4 mm. While there was a slight increase in subjects more than 8 years old the values at 10 years were, with one exception, still less than 10 mm. The increase continued but did not exceed 15 mm during the teens. After the first two decades there was a marked deterioration in the results, most of the subjects between 20 and 40 years showing values near, if not more than, 30 mm; only 2 subjects in this group, 27 and 31 years of age, had values less than 15 mm. For all those over 40 years the values exceeded 30 mm.

von Frey's hair test.

As is seen from the line diagram in Fig.

TABLE III. *Results for median nerve sutures.*

Case no.[a]	Age	Sex	Hand	Distance of suture above wrist[b] (cm)	Time from injury to suture[c] (months)	Time from suture to follow-up[d] (years)	Subjective assessment by patient[e]	Two-point discrimination[f] (cm)					
								Dig I		Dig II		Dig III	
								Rad	Uln	Rad	Uln	Rad	Uln
1	4	M	R	2	0	9½	+	4	4	3	4	4	4
2	4	F	R	0	3	11½	+	3	3	3	3	3	3
3	4	M	L	0	1	4	—N	4	3	3	3	4	5
4	5	M	R	1	6	7	—N	3	2	2	3	3	3
5	5	M	L	0	0	6½	—N	3	3	2	3	3	3
6	6	M	R	0	2½	5½	—	3	3	3	3	4	4
7	8	M	R	0	0	9½	+	4	3	5	4	6	6
8	8	M	R	1	3½	6	—N	5	6	8	8	4	6
9	9	F	R	1	3	5	++	4	5	5	5	6	6
10	9	M	R	2	1½	4	—N	3	4	4	5	4	4
11	9	F	R	1	5	5½	++	6	6	6	6	5	5
12	10	M	R	0	3½	6	—	5	7	7	5	7	7
13	10	F	R	0	0	6	—	7	9	13	11	8	9
14	10	M	R	5	2	9½	—	7	7	8	6	10	8
15	13	F	L	2	7	10	++	11	13	14	14	14	20
16	15	M	L	4	3½	7	—	7	7	9	9	10	11
17	18	M	L	2	0	11½	—	11	11	11	17	18	17
18	21	M	L	1	7	5	++	9	10	21	14	11	9
19	21	F	R	0	0	5	++	16	14	>	>	20	
20	21	M	R	0	0	10½	+++	>	>	>	>	>	>
21	24	M	L	3	0	5½	++	30	20	30	28	>	28
22	26	M	L	1	3	6½	+++	23	20	>	>		
23	27	M	L	2	0	11	+	12	9	10	17	18	15
24	31	F	R	0	4½	7½	++	9	12	12	14	17	18
25	34	F	R	0	1½	10	+	26	27	30	26	>	>
26	34	M	R	8½	5	6½	++	>	>	>	>	>	>
27	39	M	R	0	0	10	+++	9	10	26	27	28	>
28	43	M	R	0	3	5	+	28	28	>	>	30	>
29	43	M	R	0	0	7½	+	13	13	>	>	>	>
30	45	M	R	0	0	10	+++	11	21	>	>	>	>
31	46	M	L	1	0	12	+++	>	>	>	>	>	>
32	57	M	L	0	7½	10	+++	>	>	>	>	>	>

a The cases in the table are placed in order of age at operation.
b Wrist denotes the level of the distal flexor crease just proximal to the palm.
c The period elapsing between injury and nerve suture has been rounded upwards to the next half month.
d The time elapsing between the operation and the follow-up has been rounded downwards to the next half year.
e The subjective assessment has been classified according to the following four-point scale:

— No symptoms ++ Moderate symptoms
+ Minor symptoms +++ Severe symptoms

N denotes that the patient judged the sensibility within the denervated area of skin to be quite normal.

Touch[g] (g)						Five-object test[h]			Muscle waste in the thenar[j]	Pick-ing-up test[k]	Sweat index					Quotient of sweat indices dig II/V	Remarks
Dig I		Dig II		Dig III		Dig I	Dig II	Dig III			Dig I	Dig II	Dig III	Dig IV	Dig V		
Rad	Uln	Rad	Uln	Rad	Uln												
0.3	0.3	0.3	0.3	0.4	0.4	5	4	4	+	++	0.70	0.83	0.72	0.83	0.74	1.13	
0.3	0.3	0.3	0.3	0.3	0.3	3	3	3	+		1.01	0.19	0.50	0.25	0.05		Also ulnar nerve lesion
0.3	0.3	0.3	0.3	0.3	0.3	4	5	5	—	++	2.17	1.77	1.98	0.92	2.28	0.78	
0.3	0.3	0.3	0.3	0.3	0.3	5	5	5	+	++	0.60	0.91	1.72	1.36	2.21	0.41	
0.3	0.3	0.3	0.3	0.3	0.3	3	5	4	—	++	2.16	0.90	0.63	0.64	1.07	0.86	
0.3	0.3	0.3	0.3	0.3	0.3	4	4	3	+++		0.63	1.05	1.31	1.11	0.81	1.30	
0.3	0.3	0.3	0.3	0.3	0.3	4	3	3	+		0.97	0.83	0.89	0.75	0.66		Also ulnar nerve lesion
0.3	0.3	0.3	0.3	0.3	0.3				++		0.65	1.16	0.93	0.27	0.84	1.38	Mentally backward
0.8	1.0	0.6	0.7	0.6	0.6	3	1	5	+++		1.07	0.89	1.28	1.05	1.21	0.74	
0.3	0.4	0.5	0.3	0.4	0.3	4	5	4	—	++	0.96	0.94	0.67	1.18	0.93	1.01	
0.3	0.3	0.3	0.3	0.3	0.3	4	4	3	—	++	0.74	0.43	0.97	0.77	0.74	0.58	
0.7	0.6	0.5	0.4	0.5	0.6	3	2	3	+	++	0.74	1.04	1.04	0.82	0.94	1.11	
0.4	0.4	0.5	0.4	0.4	0.4	4	2	2	+		1.28	0.61	1.22	1.09	0.83	0.75	
0.7	0.6	1.8	1.1	0.4	0.5	4	4	4	++		0.60	0.48	0.46	0.79	0.70	0.69	
0.6	0.5	0.8	0.9	0.4	0.7	2	2	3	+++		1.14	0.84	1.35	2.87	1.35	0.61	
1.0	1.5	1.2	1.7	2.0	1.5	2	3	2	+	—	0.96	1.14	1.38	1.66	1.64	0.70	
0.5	1.1	0.6	0.7	0.5	0.5	4	0	2	++			3.64	2.40	3.03	3.56	1.02	
0.7	0.7	0.8	0.5	0.6		3	1	1	—	+	0.66	0.77	0.51	1.15	1.08	0.71	
2.5	2.5	2.5	>	2.5		4	1	1	—	+	0.64	0.81	1.54	0.70	0.85	0.94	
>	>	>	>	>	>	0	0	0	++		0.11	0.72	0.60	0.55	0.64	1.13	
>	2½	>	>	>	>	0	2	1	—	—	0.72	0.66	0.76	0.65	0.81	0.82	
0.7	0.3	1.2	0.9			2	0	5	+++		1.07	0.80	0.61	0.52	1.30	0.60	
0.6	0.4	0.4	0.5	0.5		3	2	0	—	+	0.42	0.76	0.44	1.39	0.78	1.12	
0.5	0.8	0.9	0.9	1.2	1.3	1	0	0	+++			0.30	0.94	0.82	1.14	0.26	
0.4	0.4	0.8	0.8	0.5	0.5	2	2	2	+	+	1.05	1.01	1.04	0.76	0.91	1.11	
1.3	2.5	2.0	1.6	1.8	1.5	0	1	1	++		0.48	0.71	0.80	1.19	1.13	0.63	
1.0	1.2	0.9	0.9	1.4		4	1	2	++		0.43	0.84	0.65	0.98	0.93	0.90	
1.8	1.6	1.3	1.3	1.0		1	1	1	+++		0.35	1.12	1.19	0.96	0.82	1.38	
1.5	1.7	1.6	2.0	1.8		3	2	0	—	—	Sweat intensity too low for calculation						
1.0	1.5	2.5	1.8	1.9		2	2	3	+	—							
2.5	>	>	>	>	>	2	2	1	+++		Sweat intensity too low for calculation						
1.5	1.2	>	>	2.0	2.0				+++								

f The values for 2 PD relate to the distal volar radial and ulnar areas of the thumb, index and middle finger. The void squares indicate that the values were unreliable owing to overlapping ulnar innervation. The sign > denotes values above 30 mm.

g > denotes values above 2.5 g.

h The figures specify the number of objects correctly identified.

j Wasting of the thenar muscles was evaluated by inspection and palpation according to a four degree scale, — to +++. No objective measurement was attempted.

k The findings were graded according to the following three-degree scale:

— Not possible + Obviously abnormal ++ Normal or almost normal

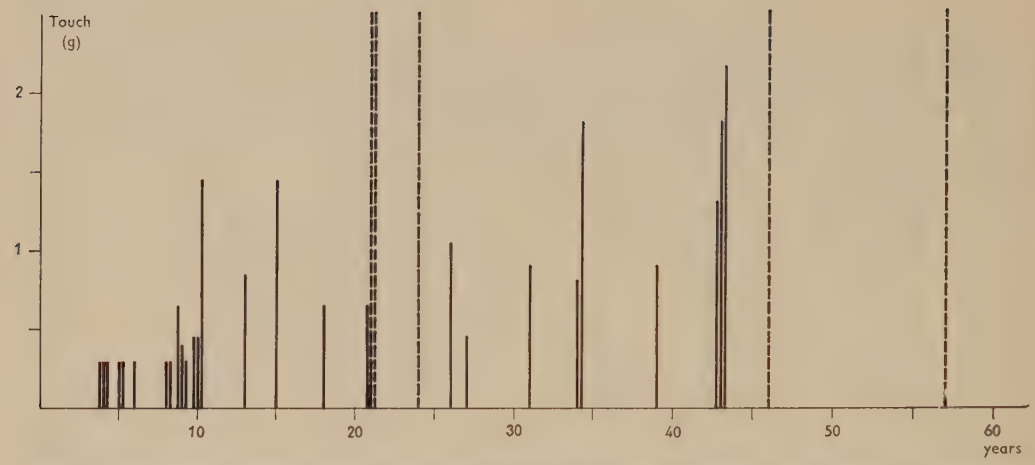


Fig 17 Median nerve sutures. Relationship between mean threshold for touch for index fingers (at follow-up) and age of subject (at suture). Each line represents one subject. The broken lines relate to values exceeding 2 ½ g.

17 based on the means for the radial and ulnar areas, there is no definite trend, but the subjects less than 9 years old all had a low touch threshold. Only 5 subjects, including the two oldest, were unable to perceive a touch stimulus of 2.5 g. Out of 32 subjects 24 perceived a stimulus of less than 1.5 g, and one older than 10 years a value of 0.5 g.

As pointed out above, von Frey's hair test has many disadvantages. To examine 'whether the results obtained with this test bore any relationship to the 2 PD values, 2 PD was plotted against touch (Fig. 18).

It is seen from the diagram that when the threshold value for touch was one gramme or more the 2 PD exceeded 30 mm. The 4 points in the lower centre part of the diagram constitute a notable exception. They relate to surfaces for which the 2 PD values were low and the threshold values for touch relatively high. One of these 2 patients was not cooperative (arrows). However, the 4 aberrant points cannot have been due to thick skin, for touch thresholds of 0.5 and 0.3 g were recorded for normal skin of these 2 subjects. On the other hand, the 40 points corresponding to 2 PD values of not more than 30 mm and a touch value of less than one gramme show a clear trend; with rising 2 PD from 3 to 30 mm the touch increases from 0.3 to 0.9; this trend is statistically significant ($P < 0.001$). The two points indicated by arrows were not included in the calculations.

Muscle wasting

Owing to the extremely inaccurate method of recording wasting of the thenar muscles the results are of doubtful value. Moreover, no account was taken of the normal anatomic variation in muscle innervation. The findings are nevertheless included since it seemed possible that this factor might be associated with sensory

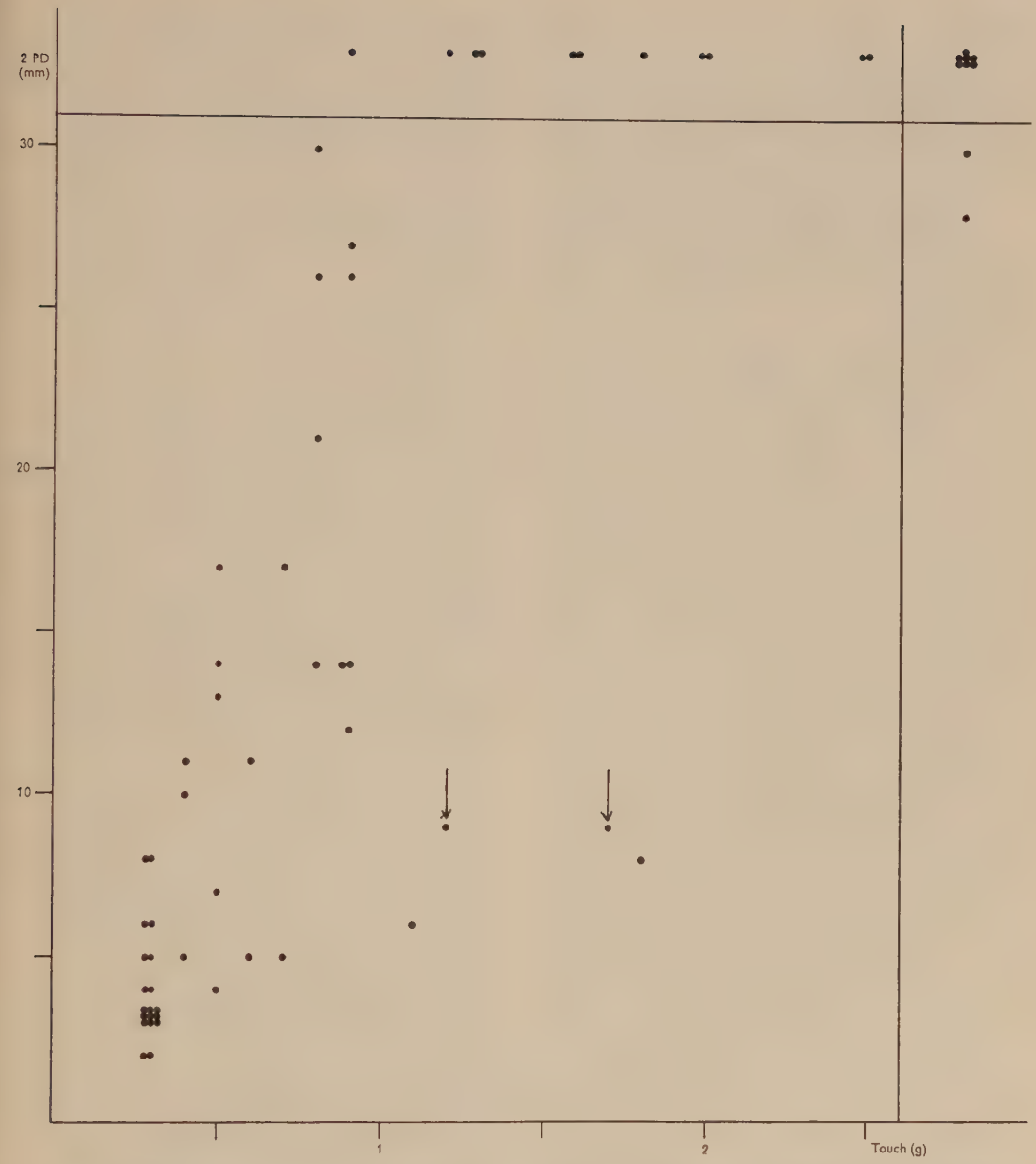


Fig. 18 Median nerve sutures. Relationship between the threshold for touch and the 2 PD for the index fingers. The values for the volar radial and ulnar surfaces are plotted separately. (67 surfaces altogether).

function. Furthermore, it was of importance as regards the picking-up test.

No definite relationship between muscle wasting and the other functions tested was found; nor was there evidence of a close link with the patient's assessment of symptoms.

Picking-up test

The results relate to 15 cases with no notable wasting of the thenar muscles. The motor component in these cases may be assumed to have exerted no more than a small unfavourable effect on the test.

Table III illustrates a practically perfect picking-up test by 7 subjects for whom the maximum 2 PD for the index finger was 6 mm.

In 4 cases showing 2 PD values of 18, > 30, 14 and 28 mm the picking-up test indicated obvious abnormality though the patients managed to pick up the objects. In the second case a value of 15 mm for the thumb may explain the unexpected ability to pick up small things at all (Mannerfelt, 1962), but in the last case the values for the thumb and index finger were practically identical; it may be noted that in this case there was some doubt as to whether the results of the picking-up test should be classed as + or —.

Four patients found it extremely difficult or impossible to pick up the objects. The 2 PD for the index fingers was 29 mm in one case, > 30 mm in 2, and 9 mm in one. The last patient (no. 16) is the 22-year-old for whom there was a poor relationship between 2 PD and touch. It is notable that he did up buttons strikingly well, a more difficult operation than that involved in the picking-up test.

Five-object test

This test provided extremely capricious results. Only one subject was able to recognize all 5 objects with all 3 digits innervated by the median nerve. In general the younger subjects found it easier to recognize the objects. For those giving three correct answers the 2 PD values rarely exceeded 10 mm.

The test would seem to be unreliable. It is possible that the memory had some influence, and in some cases the vibrations caused by stroking with the object may have been conducted to normally innervated regions. Auditory impressions may also have had some influence.

Sudomotor activity

The sweat function was expressed in terms of the relationship between the injured and the normal sides. Unlike the 2 PD values these sweat indices displayed a wide variation (up to 6 times the lowest value) in the same median nerve area (Table III). It was decided to take the sweat index for the forefingers as representative of the median region, as in the case of the 2 PD, thus ensuring that the prints were taken from zones innervated only by the median nerve.

For 6 of the 28 cases with measurable secretion the sweat index was below the normal range of variation (0.67—1.50), while for 2 cases this range was exceeded. Twenty subjects had an index within the normal limits—lower than 1.0 in 14 cases and higher than 1.0 in 6 cases.

As Table III shows, there was no definite relationship between the sweat index and the results of any of the other tests. This is contrary to expectation, and may be due to special circumstances. After severance of a nerve there is complete anhidrosis, and on the surrounding normal skin there is often hyperhidrosis—perilesionary hyperhidrosis (Guttmann & List, 1928; Foerster, 1929; Guttmann, 1929, 1931). From a purely theoretical standpoint it is not unreasonable to suppose,

however, that if this tendency for hyperfunction persists after re-innervation of the sweat glands in the anhidrotic regions, hyperhidrosis also might appear in these previously denervated areas. This might explain the occasional occurrence of hyperhidrosis in the median nerve region after regeneration of the sensibility. Moreover, asymmetric secretion (p. 31) may influence the values in either direction.

Within the framework of this investigation it is the sweat index only for the little finger that, on the volar aspect of the hand, might provide information on the perilesionary hyperhidrosis or asymmetric sweating. When the 2 cases with combined median-ulnar nerve suture are excluded there remain 26 cases that are suitable for comparison of the indices for the fore- and little fingers. In 21 of them the index for the little finger was within the normal range of variation (0.67—1.50), 14 of them below 1.0 and 7 above. In one case (no. 20) it was below the normal range, at 0.64; however, the fact that the indices of the other digits also showed low values suggests the possibility of general hypohidrosis of the injured hand. In 2 out of the 4 cases with a high sweat index for the little fingers high values were recorded also for the 3 radial digits; this may be have been due to hyperhidrosis on the side of the suture or hypohidrosis on the normal side. In the other 2 cases a high index was recorded for some but not all of the radial digits.

The effect of unilateral hypo- or hyperhidrosis on a particular digit may be largely eliminated by dividing the index for this digit by the index for the little finger. In the case of the forefinger, the quotient so obtained lay within the normal limits of variation in 5 of the 7 cases for which the sweat index lay outside the normal range of variation.

This quotient may provide a more accurate representation for all cases. Any moderate but consistent unilateral hyposecretion, as was found for 4 subjects, would then be compensated for. These revised sweat indices are entered in Table III. It may be noted that in no case is this quotient greater than 1.50, in 10 cases it lies between 1.50 and 1.0 and in the same number between 1.0 and 0.67. In 6 cases it is below 0.67, and in these hyposecretion may be assumed to have been present. As was found in respect of the original sweat index for the forefingers, these new quotients are not correlated with the 2 PD values.

ULNAR NERVE SUTURES

Table IV provides a summary of the results of the 17 ulnar nerve sutures. It has been compiled on the same lines as the table for the median nerve sutures.

Subjective assessment

Eight subjects, aged 4—26 years at operation, stated that they experienced no symptoms (—). Four of them considered that there was no difference in sensibility between the ulnar region and the surrounding area; they were all 4 or 5 years of age at operation and at least 10 years at the follow-up. The other 4, who were older at operation, were aware of some change in sensibility in the ulnar region.

TABLE IV. *Results for ulnar nerve sutures.*

Case no.[a]	Age	Sex	Hand	Distance of suture above wrist[b] (cm)	Time from injury to suture[c] (months)	Time from suture to follow-up[d] (years)	Subjective assessment by patient[e]	2 PD (mm) for dig V		Touch (g) for dig V		Five-object test for dig V[h]	Muscle waste	Sweat index					Revised sweat index for dig V[m]		Remarks
								Rad	Uln	Rad	Uln			Dig I	Dig II	Dig III	Dig IV	Dig V			
33	4	F	R	0	3	11½	+	3	3	0.3	0.3	3	+	1.01	0.19	0.50	0.25	0.05			Also median nerve lesion
34	4	F	R	12	4	7	—N	5	5	0.3	0.3	4	+		1.01	1.01	1.01	0.56	III	0.55	
35	5	M	L	4	0	7	—N	4	5	0.3	0.3	5	+		1.00	0.98	0.85	0.90	III	0.92	
36	5	M	R	0	0	10½	—N	3	3	0.3	0.3	5	—	0.99	1.04	1.15	0.54	0.80	II	0.77	Also partial lesion of median nerve
37	5	M	R	0	0	5	—N	4	4	0.3	0.3	5	—		1.00	1.16	0.69	1.77	III	1.53	
38	6	M	L	0	0	5	—	4	5	0.3	0.3	5	++	0.70	0.96	0.94	0.90	1.20	II	1.25	Also partial lesion of median nerve
39	8	M	R	0	0	9½	+	5	7	0.3	0.3	4	+	0.97	0.83	0.89	0.75	0.67			Also median nerve lesion
40	10	M	R	1	1½	6½	+	8	8	0.4	0.5	5	—			0.85	1.05	0.80	III	0.94	
41	11	F	L	3	0	10	—	22	17	0.5	0.5	1	++	1.14	1.87	1.58	0.81	0.68	III	0.43	
42	14	M	L	0	0	5	+	9	5	0.3	0.3	3	—	0.88	1.20	1.51	1.21	0.81	III	0.54	
43	17	F	L	3	0	5	—	14	12	0.4	0.3	3	+	1.61	1.34	1.24	1.14	1.47	III	1.19	
44	17	M	L	2	0	6	++	12	12	0.3	0.3	2	++	0.55	0.93	0.60	0.57	0.99	III	1.65	
45	26	F	L	0	2	5	—	6	4	0.3	0.3	4	—		1.27	1.08	1.12	1.08	III	1.00	
46	33	F	L	3	0	5½	+++	>	>	2½	2½	0	++	1.05	1.35	0.88	0.32	1.13	II	0.84	
47	41	M	R	1	0	9	+++	>	>	1.4	1.5	0	++		1.08	1.17	0.82	0.48			Also partial lesion of median nerve
48	42	M	L	13	1½	7½	+++	>	>	1.6	1.0	1	—	Sweat intensity too low for calculation							
49	45	M	L	1	6½	7	+++	>	>	>	>	0	+++	0.50		0.29	0.67	0.06	I	0.12	

For key to footnotes *a*—*e* and *h* see Table III.

m The quotient of the sweat index for dig V by that for the nearest finger with unimpaired sensibility (Roman numerals).

Four patients, aged 4—14 years, had mild symptoms (+) that may have been due to impaired sensibility.

The only patient with moderate symptoms (++)—aged 17 at operation—was often reminded of his injury in his daily routine and tended to avoid using the ring and little fingers.

Four patients aged 33—45 years experienced considerable discomfort from the injury (+++). They did not use the two ulnar fingers, which were highly sensitive to cold. Sometimes the hand was painful and affected by cramp. These subjects were the 4 oldest at operation.

After ulnar nerve sutures the patients find it difficult to distinguish between symptoms due to impaired sensibility and those due to incomplete motor regeneration.

Two-point discrimination

The line diagram showing the results of the two-point discrimination tests is based on the values for the little finger—the mean for the radial and ulnar surfaces

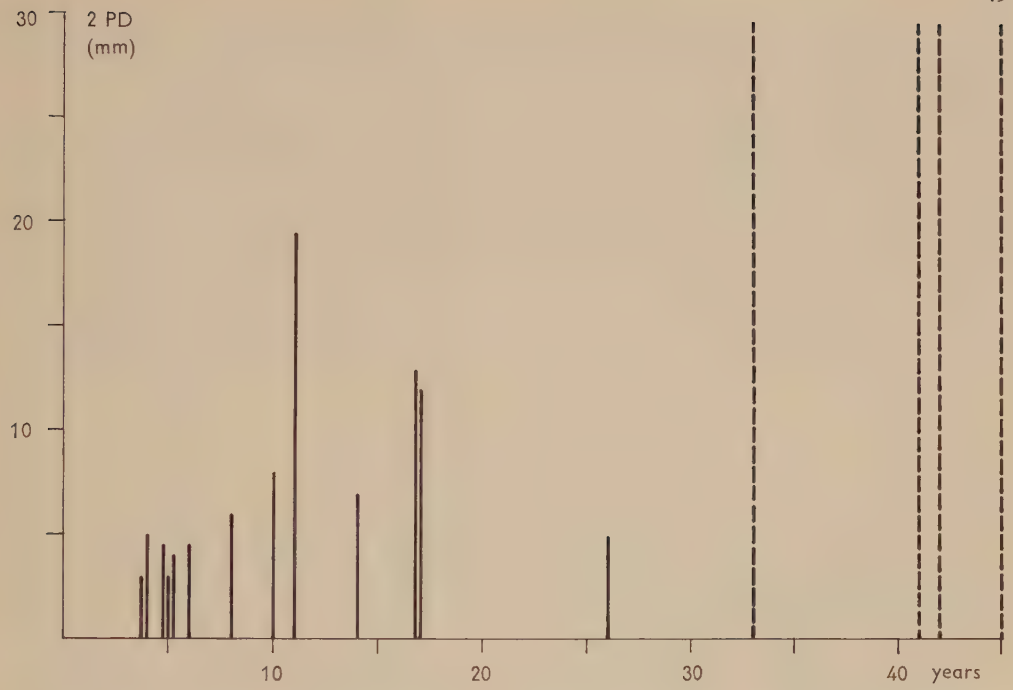


Fig. 19 Ulnar nerve sutures. Relationship between mean 2 PD values for little fingers (at follow-up) and age (at suture).
Each line represents one subject. The broken lines relate to 2 PD values exceeding 30 mm.

(Fig. 19). The values for these two surfaces were very similar except in 2 cases where the differences were 5 and 4 mm.

In spite of the small number of subjects in this group of ulnar nerve sutures the association between two-point discrimination and age is evident. If case 41 with unexpectedly high 2 PD values and case 45 with extremely low values are disregarded, the tendency is the same as for the median nerve group. For the sutures performed in the first 6 years of life the maximum 2 PD was 5 mm; at 10 years it was still below 10 mm, and exceeded this level only in the teens. For the four sutures performed on patients over 30 years of age the 2 PD values were greater than 30 mm.

von Frey's hair test

The values presented graphically in Fig. 20 are the means for the radial and ulnar surfaces of the little finger. For subjects up to 30 years of age at operation the threshold was not more than 0.5 g, corresponding to a maximum 2 PD of 19.5 mm. After this age the minimum threshold was 1.3 g and the 2 PD exceeded 30 mm.

Five-object test

For the ulnar nerve sutures there was a relationship between the results of 2 PD and the five-object test. Four or 5 correct answers were given by 8 out of the 10 subjects having a 2 PD of not more than 8 mm. All the subjects with poor dis-

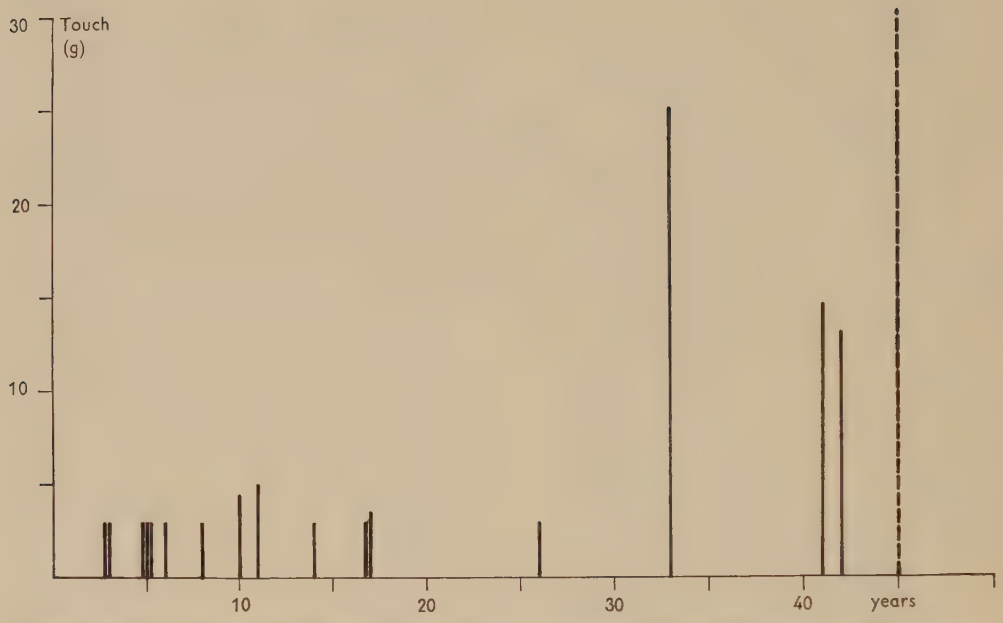


Fig. 20 Ulnar nerve sutures. Relationship between mean threshold for touch for little fingers (at follow-up) and age (at suture).
Each line represents one subject. The broken line relates to value exceeding 2½g.

crimination also showed poor results in this test.

Muscle wasting

Muscle wasting was most pronounced in one case—the oldest of the patients. In 5 cases the loss was moderate and in 5 mild; in 6 there were no definite signs of wasting. In spite of an almost normal muscle mass there was only one patient out of these 6 who recovered the power to adduct the little finger. This means that in spite of good re-innervation of the muscles they did not recover independent function. There was no evident relationship between muscle wasting and sensory function.

Sudomotor activity

Since only the little fingers are consistently innervated by the ulnar nerve it is their sudomotor activity alone that can be considered representative of the ulnar region. The sweating was acceptable for 16 out of the 17 cases. In 11 cases the values lay within the range 0.67—1.50, with 7 below 1.0 and 4 above; in one case it was above this range at 1.77, and in 4 cases it was below, the lowest value being 0.06.

The sweat index for the 3 radial digits showed a smaller intra-subject variation in these cases of ulnar nerve sutures than in the cases of median nerve sutures. Any residual perilesionary hyperhidrosis would then be an increase in the values from the thumb towards the little finger. Such an increase was in fact noted in case 42, but case 43 displayed a rise in the opposite direction. Accordingly, there

were no signs of perilesionary hyperhidrosis.

In asymmetric sudomotor activity the sweat index is consistently low or high. Cases 43 and 49 showed such a tendency.

There was no essential change in the revised sweat index (last column of Table IV). It is true that within the fairly little affected extreme values there is some regrouping but 4 still lay below 0.67. Two were slightly above 1.50. This would suggest that in 4 cases there was hypohidrosis and in 2 cases slight hyperhidrosis.

For none of the individual subjects was there a relationship between either 2 PD or touch and the primary or revised sweat index for the little fingers. As was found for the median nerve sutures, however, there was a certain general tendency to hypohidrosis on the sutured hand.

DIGITAL NERVE SUTURES

The results relating to digital nerve suture are given in Table V on the same lines as for the median and ulnar sutures.

The prints for the digital nerve sutures differ from the others in that they were taken from an area of skin the sweat secretion of which was regulated via two nerve sutures. This was a compromise solution which was preferred to an attempt to take prints from the area of innervation of each digital nerve. In no case was there any distinct difference in the number of dots on the two halves of the prints.

Subjective assessment

Eight patients, aged 3—15 years and among the 9 youngest at operation, were classed as symptom-free (—) in respect of sensibility. Four considered the sensibility to be entirely normal in the area earlier denervated.

In 5 cases, aged 8—48 years at operation, there were mild symptoms (+). In one case the injury involved the forefinger and in 3 others the thumb.

Moderate symptoms (++) were noted in 3 cases in which the sutures were made at the age of 29, 30 and 47 years.

In 6 cases there were severe symptoms (+++), the sensibility being so poor as to be considered valueless except for protection against injury.

The inevitably rough nature of the classification should be borne in mind.

Two-point discrimination

The results of the two-point discrimination tests are presented in Fig. 21. The line diagram represents the means for the radial and ulnar areas. Since the sensibility on the two areas is dependent on different nerve sutures fairly large differences might be expected. The largest differences were 8, 6 and 3 mm for one case each, and only one of the remainder was greater than 2 mm. The differences are thus similar to those for the median suture.

The 4 patients undergoing operation before reaching their eighth year were able to discriminate between points 2—3 mm apart. For the 4 cases aged between 8 and 11 years the means were slightly higher, up to 5.5 mm. One subject of 15

TABLE V. *Results for digital nerve sutures.*

Case no.[a]	Age	Sex	Hand	Digit tested	Distance of suture from finger-tip (cm)	Time from injury to suture[c] (months)	Time from suture to follow-up[d] (years)	Subjective assessment by patient[e]	2 PD (mm)[n]		Touch (g)		Five-object test[h]	Sweat index[o]					Revised sweat index[p]		Remarks
									Rad	Uln	Rad	Uln		Dig I	Dig II	Dig III	Dig IV	Dig V			
50	3	F	R	V	10	5	5½	—N	3	3	0.3	0.3	5		1.17	1.18	1.67	*0.69*	III	0.59	Suture of superficial branch of ulnar nerve
51	4	M	L	III	10	0	4	—N	3	3	0.3	0.4	4	0.65	0.87	*0.70*		0.76	V	0.91	Suture of common digital nerves
52	6	M	R	II	3	3	8	—	2	2	0.3	0.3	4	0.92	*1.09*				III	0.84	
53	7	M	L	V	8	0	5	—	2 B	2	0.3	0.3	5	0.77	0.98	0.57	0.63	*0.14*	III	0.25	Suture of superficial branch of ulnar nerve
54	8	F	R	V	18	6	9½	+	5 B	5	0.3	0.3	5	1.03	0.17	1.71	1.17	*0.41*	III	0.24	Suture of superficial branch of ulnar nerve
55	9	F	R	I	10	3	5	—N	3 B	3	0.3	0.3	5	*1.07*	0.83	0.64	0.77	0.78	II	1.29	
56	10	F	R	IV	3	0	10	—	5 B	5	0.3	0.3	1		0.83	0.99	*0.92*	0.89	III	0.93	
57	11	M	R	III	9	3	6½	—N	5	6	0.4	0.4	2	1.95	9.09	*1.76*	1.05	1.07	I	0.90	Suture of digital nerves of all four fingers
58	15	F	L	I	12	7	6	—	8 B	16	0.3	0.4	1	*0.99*	1.76	1.30	0.92	1.04	III	0.76	Suture of common digital nerve
59	15	F	R	I	10	0	8½	+++	19 B	25	0.8	1.0		*1.39*		1.29	1.13	0.77	III	1.07	
60	22	M	L	I	9	7	11	+	6 B	7	0.5	1.1	2	*0.74*		0.99	1.01	0.77	III	0.75	
61	23	F	R	V	13	0	12½	+++	>	>	>	>	0	0.86	0.77	1.22	1.13	*0.65*	III	0.53	Suture distal to division of superficial branch of ulnar nerve
62	29	M	L	IV	5	2	8½	++	9 B	12	0.3	0.3	1		1.98	1.90	*2.04*		II	1.03	
63	30	M	L	V	8	2	10	++	18	16	0.3	0.3	3	1.05	1.71	1.40	1.06	*0.89*	III	0.64	
64	35	M	L	II	7	4	15½	+	20	22			1	0.98	*0.37*	1.32			I	0.38	Saw lesion
65	39	F	R	I	7	0	6	+	10	8	0.7	1.0	3	*0.74*	0.75	0.82	0.90	0.72	II	0.99	
66	46	M	R	I	4	0	5	+++	>	>	>	>	0	Sweat intensity too low for calculation							
67	47	M	R	II	5	1	11	++	11	10	0.5	0.5	1								
68	48	M	L	I	5	3	7	+	13 B	12	0.8	1.0	4	*0.24*	0.72	1.23	0.87		II	0.33	
69	49	M	L	I	7	7	6	+++	19 B	21	0.6	0.9	2	Sweat intensity too low for calculation							
70	67	F	L	V	12	0	7½	+++	>	>	>	>	0								Suture of superficial branch of ulnar nerve
71	68	M	L	II	5	0	8½	+++	28		>	1.5	0.9	0	Sweat intensity too low for calculation						

For key to footnotes *a*, *c*—*e* and *h* see Table III.

n B denotes blocking of dorsal finger sensibility.

o Sweat index for tested finger in italics. Voids indicate amputated digits, digits with scars on the pulp, or with partial nerve lesion.

p The quotient of the sweat index for the tested finger by that for the nearest finger with unimpaired sensibility (Roman numerals).

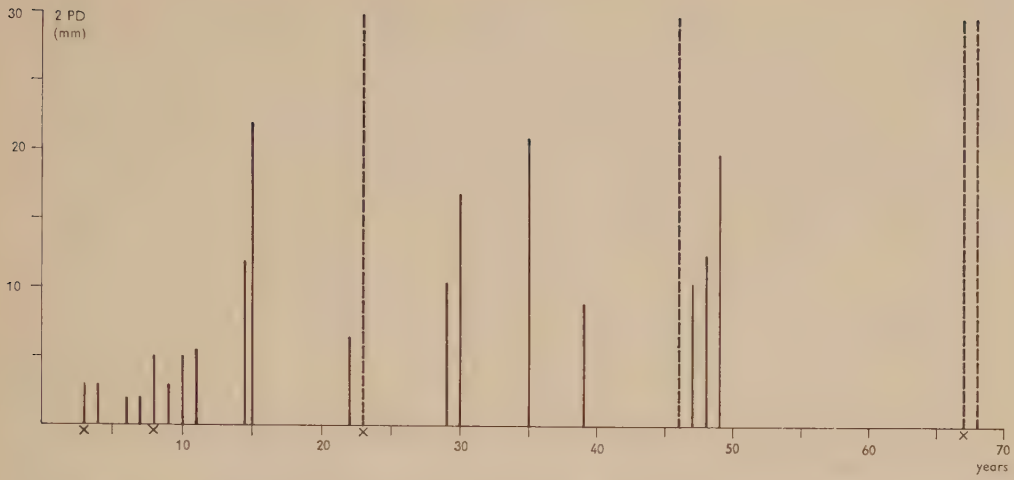


Fig. 21 Digital nerve sutures. Relationship between mean 2 PD value for the tested finger (at follow-up) and age (at suture).

Each line represents one patient. The broken lines relate to 2 PD values exceeding 30 mm. The crosses immediately below the abscissa indicate the cases of suture of the superficial branch of the ulnar nerve.

years could not do better than 22 mm. Of the 12 patients between 22 and 68 years there were only 4, aged 23—68, that had 2 PD values greater than 30 mm; the other values were fairly uniformly distributed between 6.5 and 21 mm and were unassociated with age. The 6.5 mm value was recorded for a 22-year-old man and the 9 mm for a woman of 39 at operation.

The results for adults after suture of the digital nerves are notably better than those for the median and ulnar nerve sutures. This difference may be to some extent due to intact dorsal innervation in the case of digital nerve injuries and transmission to the dorsal receptors of stimuli applied to the volar aspect.

As these possibilities were overlooked at first, 10 subjects were re-examined after the dorsal innervation had been blocked. In no case was the power of discrimination notably poorer. On the whole, the 2 PD values may therefore be considered to provide a measure of the regenerated sensibility.

von Frey's hair test

The younger subjects up to 15 years of age recorded low values not exceeding 0.4 g. Thereafter the values varied arbitrarily with age (Fig. 22). On the other hand, there seemed to be a close parallel with the 2 PD values. In Fig. 23 2 PD is plotted against touch; with 2 unimportant exceptions, values greater than 30 mm were associated with touch thresholds of more than one gramme. For values below 30 mm the touch threshold did not exceed one gramme—save in one case. As the 2 PD value increases from 3 to 30 mm the touch threshold tended to increase from 0.3 to one gramme. The correlation between touch and 2 PD is statistically significant ($P < 0.001$).

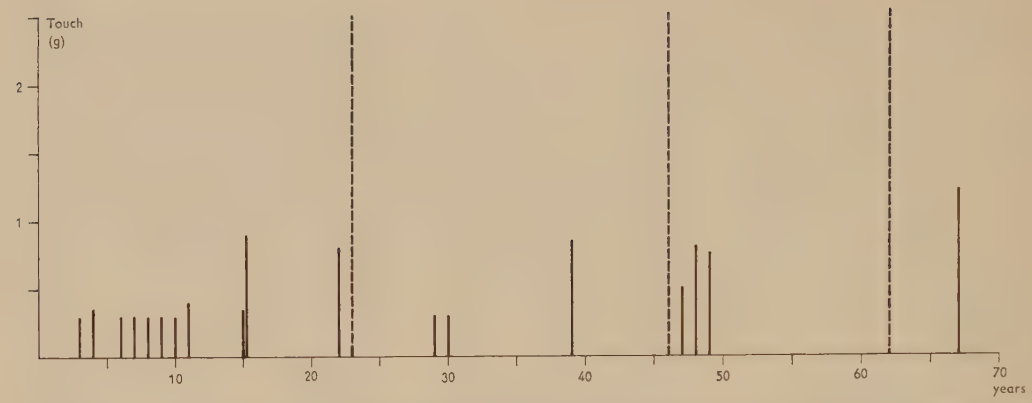


Fig. 22 Digital nerve sutures. Relationship between mean threshold for touch for tested finger (at follow-up) and age (at suture).
Each line represents one subject. The broken lines relate to values exceeding 2½ g.

Five-object test

The results of this test show a fairly close association with those of the 2 PD tests. The parallel is not complete and it is evident that the test did not provide more information than was obtained from the other tests.

Sudomotor activity

For only 17 out of the 22 subjects was the sweat secretion great enough for quantitative study. The remaining 5 were among the 6 oldest. In 10 cases the sweat index for the injured finger was within the normal range (0.67—1.50) with 7 less than 1.0 and 3 greater; in 2 cases the value was above the upper limit, with values of 1.76 and 2.04, and in 5 cases below the lower limit, with a minimum of 0.14. There was no evidence of an association between the sweat index and the 2 PD value.

The quotient of the original sweat index by the index for the closest finger with unimpaired sensibility differs in some cases from the original index; the disappearance of the high values in cases 57 and 62 indicates that there was left-right asymmetry in sweating. The subnormal values remain low and are increased by 2. In general there is a slight displacement downwards and there is a tendency for hypohidrosis on the sutured fingers. In the individual case, however, no definite relationship between the revised sweat index and the 2 PD value can be detected.

In case 57 in which the digital nerves of the 4 fingers were sutured there is an exceptionally high sweat index of 9.09 for the forefinger; the curve for the normal forefinger is much lower than the others. The only reasonable explanation of this would seem to be that the normal finger was injured or infected some time before the examination, although the patient denied this and no signs of injury were observed. The plausibility of this explanation is enhanced by the findings for another case with pronounced but obscure hyposecretion for one finger; however, when almost invisible scars were discovered this subject recalled that the finger in question had received an injury a month or so previously.

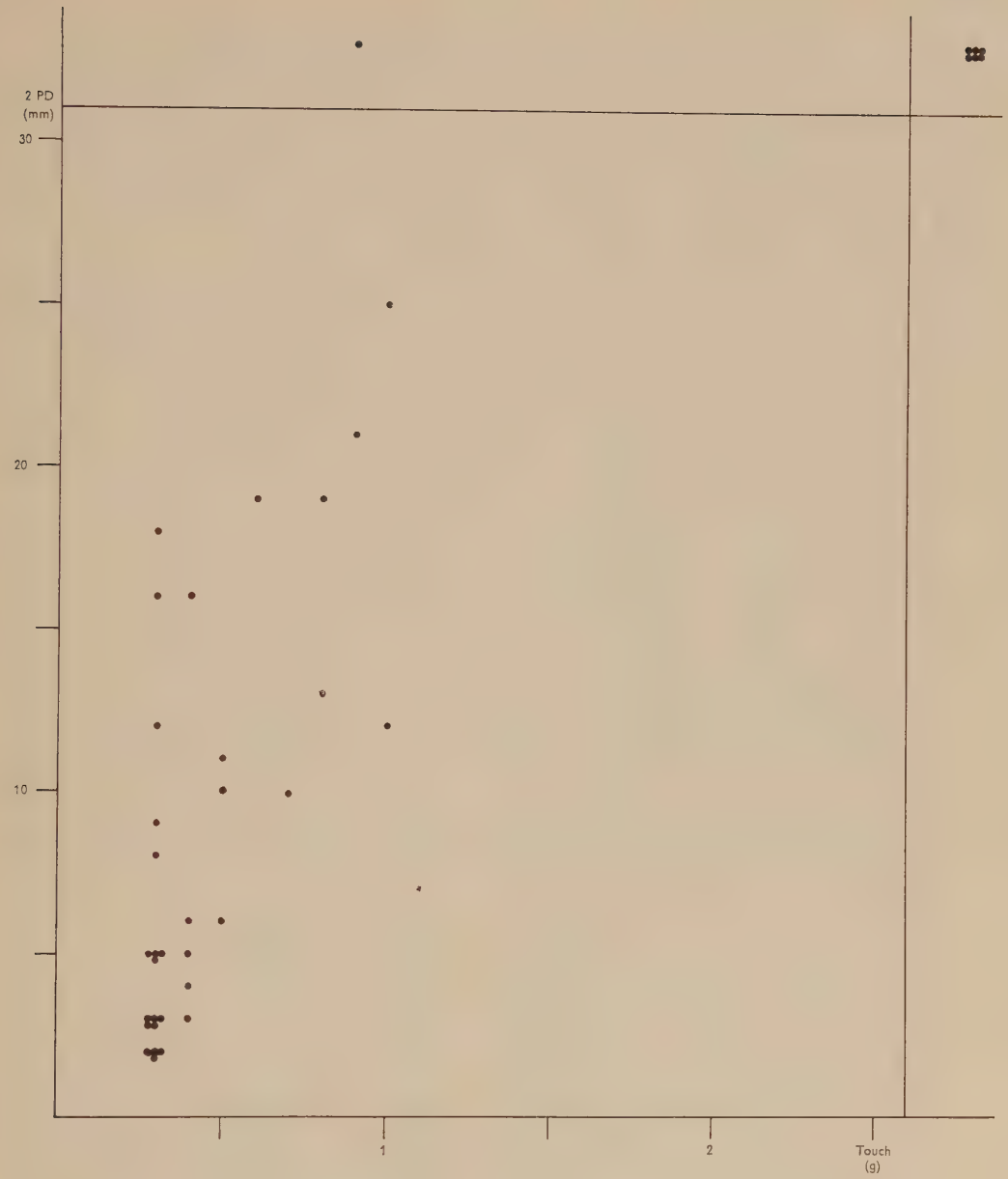


Fig. 23 Digital nerve sutures. Relationship between the threshold for touch and the 2 PD. The values from the volar radial and ulnar surfaces are indicated separately (44 surfaces altogether)

PRIMARY AND SECONDARY NERVE SUTURES

To explore the possibility of a difference between the end results after the 24 primary and 25 secondary sutures of the median and ulnar nerves, the 2 PD values were recorded in graphical form (Fig. 24). The digital nerve sutures have been omitted from the figure for the sake of clarity. No appreciable difference between the groups is evident from the line diagrams.

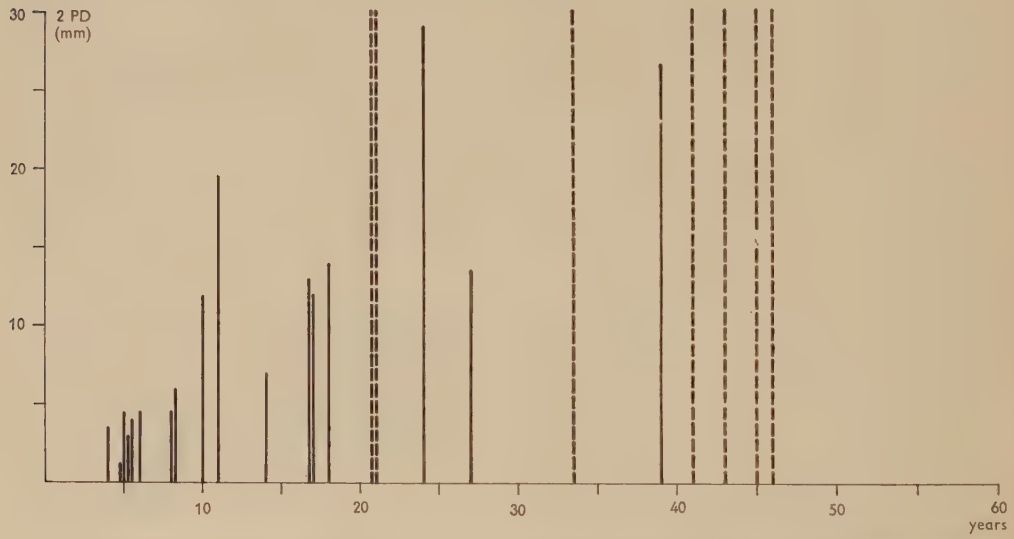
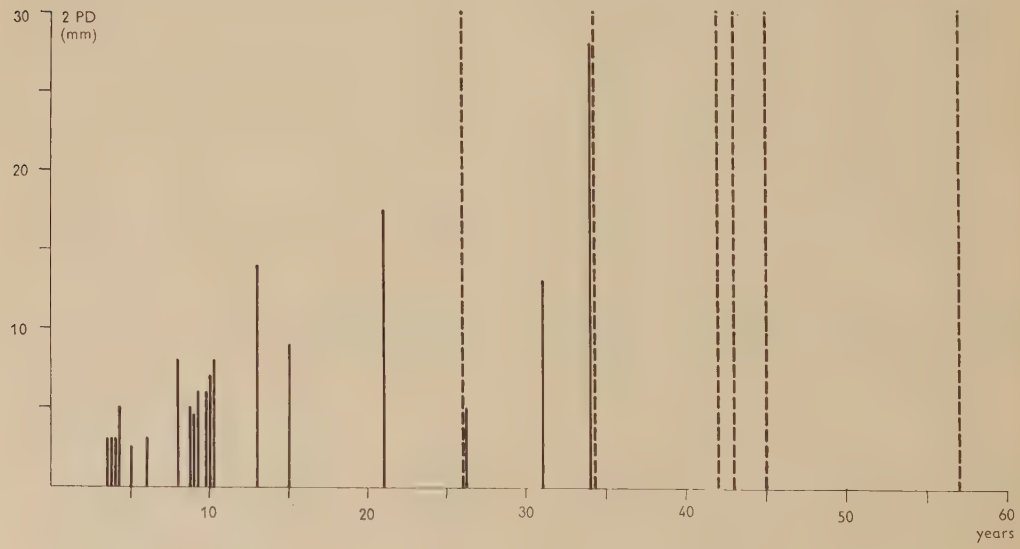


Fig. 24 Relationship between mean 2 PD values (at follow-up) and age (at suture). A, Primary sutures.



B, Secondary sutures. There is no distinct difference between the two groups.

DISCUSSION

SUBJECTIVE ASSESSMENT

The hand has a remarkable capacity for compensating for defects, including limited loss of sensibility. The subjective assessment of symptoms resulting from an injury to the hand is dependent largely on the extent to which it is used in work, and on other factors such as the mental attitude of the patient and his power of habituation. For this reason a loss of function that is not assessed as being particularly serious by one person may be considered of great importance by another.

Because the patient's evaluation of recovery is inevitably based only on subjective symptoms, it can hardly provide a logical foundation for judging the results of an operation, or the relative value of different methods of testing. It is possible that a patient who considers himself to be free of symptoms after a nerve suture may have felt the same if no operation had been performed.

This argument may be illustrated by two examples. Case 28, a business man, reported only quite mild subjective symptoms after a median nerve suture although he was quite incapable of picking up small objects blindfolded with the involved fingers, the 2 PD values for which were about 30 mm or more. The second example, case 11, was a 15-year-old girl who was at school and helped with a variety of household duties, all requiring a high quality of sensibility in the dominant hand. She stated that she had moderate trouble from the hand in which the suture was performed. She nevertheless performed the picking-up test remarkably well and was able to discriminate points only 6 mm apart.

It should be borne in mind that an absence of subjective symptoms does not necessarily mean that the patient considers the sensibility to be quite normal. In this investigation complete absence of symptoms was recorded after only 5 median and 4 ulnar nerve sutures and in 4 cases of digital nerve sutures. None of these 13 patients were more than 11 years old at the time the sutures were performed, and in only one case—that of a mentally backward youth—did the 2 PD value exceed 5.5 mm, and then it was 8 mm.

A further 14 patients (6 median and 4 ulnar nerve sutures and 4 cases of digital nerve sutures) stated that they experienced no symptoms, although they were aware of some change in the quality of the regenerated sensibility. Their ages at operation ranged from 6 to 26 years and the 2 PD values from 2 to 20 mm. This last value was noted on a little finger 10 years after an ulnar suture had been performed. The highest value among the median suture cases in this group was 14 mm and was recorded for a man engaged in heavy work. Thus, the group provides several examples of inconsisten-

cy between the subjective symptoms and the results of the tests.

The groups with mild and moderate symptoms displayed a wide range of 2 PD values. On the other hand, the patients that considered the sensibility to be poor also showed poor test results; in 13 out of 16 cases composing this last group the 2 PD was greater than 30 mm.

SIGNIFICANCE OF AGE

Divergent views have been expressed on the influence of age on the regeneration of sensibility. A number of workers have found no evidence that age is of prognostic importance (Ehalt, 1938; Marble *et al.*, 1942; Hamlin & Watkins, 1947; Björkesten, 1947), while others have considered that nerve sutures gave better results for children than for adults (Elkington, 1944; Zachary & Holmes, 1946; Sunderland, 1949; Larsen & Posch, 1958). Sakellarides (1962) found that the results were excellent or good for 82 per cent of persons under 16 years, against 42 per cent of those over 16. Nicholson & Seddon (1957) reported "adequate sensory recovery" for all 23 distal sutures of the median and ulnar nerves in the age group 0—10 years. Four out of 7 patients more than 50 years old followed for more than 3 years recorded adequate sensory recovery — that is "good localization of stimuli and some return of two-point discrimination", The last-mentioned figures may be considered to indicate that if the requirements are reduced for what may be considered to be a satisfactory level of sensibility, more cases would fall in this grade but at the same time the difference between the age groups would be less significant.

Zrubecky (1960) had no instance of poor recovery of sensibility after digital nerve sutures on children under 10 years. Stromberg *et al.* (1961) found that after nerve sutures distal to the middle of the forearm the 2 PD recovered to normal (5 mm) or practically normal for all children up to 10 years of age.

Zachary (1954), on the other hand, had not seen any case of recovery to absolute normal after median or ulnar sutures.

In none of the follow-up studies mentioned are exact data given on the value of the 2 PD nor on the performance of the test or what threshold was used. These results are therefore not comparable with those of the present study.

A consistent feature in all three types of nerve sutures of the present series is the close relationship between age and the 2 PD value. All the patients up to 6 years of age undergoing operations recovered to the extent that the 2 PD never exceeded 5 mm, and usually differed little from the normal value. Up to 10 years of age there was only one patient with a 2 PD considerably above 10 mm—in the other cases it was less than this.

The discriminative power gradually deteriorated with age at operation. Roughly speaking, the 2 PD value in millimetres corresponded to the patient's age up to 20 years. For patients between 20 and 30 years at operation the results varied but were mainly on the poor side. After 30—35 years the results were poor for all cases of median or ulnar sutures—the 2

PD approaching or exceeding 30 mm. On the other hand, the digital nerve sutures showed fairly good recovery of 2 PD up to 50 years or so.

It is consistent with general experience that all healing processes are better the younger the subject. It has been shown experimentally that the latency period in a nerve suture line is shorter and that the sensibility regenerates more rapidly in younger than older rabbits (Gutmann *et al.*, 1942; Gutmann & Guttmann, 1942). Moreover, during regeneration the distal stump contains more axons in the young animal (Midana, 1930). It is not known whether the fibre diameter and the conduction velocity recovers better in younger subject, but in any case these two quantities are never normal in sutured nerves of adult cats (Berry *et al.*, 1944; Berry & Hinsey, 1946).

There is thus reason to suppose that the local conditions at the site of suture and perhaps also in the peripheral stump are more favourable in children than adults. On the other hand, there is no evidence that in the younger subjects the nerve fibres more readily find the path to their original Schwann sheaths. The extent to which fibre-shunting occurs is probably the same at all ages. That function may be recovered at all after a nerve suture is in itself remarkable, and may be due to the fact that of all the nerve fibres reaching the periphery only the most suitable survive (Sperry, 1945). In spite of this there is certainly an extensive misdirection of nerve fibres.

Recovery of function presumably involves some central nervous re-organization. The findings of the present study suggest a fairly good possibility of re-education up to 7 years of age, after which it falls off until, after 15 to 20 years, it is very limited. The faulty sensory localization that is found several years after a suture (Hawkins, 1948) is a sign of a central fixation of the cutaneous sensibility. The extent of this fixation is unknown, however. Sperry (1945) considers that there is very little possibility of central adaptation, a view that is not shared by Gutmann (1958). The significance of age has been discussed in detail only by Weiss (1950), who speaks of "progressive fixation of nerves with age"; but he is referring here to the lower vertebrates.

It is not clear what conclusions are to be drawn from the slightly better results in adults for digital than for median and ulnar nerve sutures. The difference can hardly be ascribed to irrelevant factors. It may be that the central nervous re-organization is easier after digital nerve sutures because of the smaller areas of skin involved. Fibre-shunting can never result in the connection of an outgrowing axon with an end organ that is as far away from the original end organ as it is after a median nerve suture.

UNIFORMITY OF REGENERATED SENSIBILITY

There is a fairly close agreement between the 2 PD values for the three radial digits efter median sutures. Most of the major deviations relate to the thumb, which in 5 cases displayed better values, but never worse than one millimetre.

The majority of the median sutures were at the level of the wrist—that is, some centimetres proximal to the site of branching. On the segment of the nerve trunk distal to the suture there is no actual re-grouping of the nerve fibres between the bundle groups representing the terminal branches (Sunderland, 1945). Performing sutures on cadavers and examining them under the microscope, Edshage (1961) found a wide discrepancy between the histologic picture and the gross appearance. Several fascicles in one nerve end were not in contact at all with the opposed nerve end. The same conditions may be considered to occur in the living subject. Moreover, a clot between the nerve ends may prevent the sprouting axons from reaching the distal stump. Such local factors would account for any differences in regeneration of the sensibility between the fingers served by a particular nerve. However, no pronounced variations were found except in the thumbs of 5 subjects. The explanation for the uniform regeneration may lie in the nature of the process itself. The axons growing from the proximal stump give rise to a rich and complex arborization forming a cicatricial plexus at the site of the suture (Cajal, 1928). It is conceivable that this plexus formation will result in a fairly homogeneous distribution of the axons reaching the peripheral stump. On the other hand, no large diastasis can be bridged.

After ulnar sutures there was a particularly close agreement between the 2 PD values for the radial and ulnar halves of the pulp of the little finger. It is conceivable, though not very likely, that the difference between the two halves is greater than the figures indicate, but that the difference is masked by a transmission of stimuli from the poorer part to the better on testing the former.

After digital nerve sutures, too, the 2 PD values were with few exceptions closely alike for the radial and ulnar halves of the finger pulps. This is remarkable in view of the fact that the nerve fibres of these two halves pass through different nerve sutures. Here too, the explanation may lie in the transmission of stimuli by the tissues from one side to the other, though, again, this would seem to be rather improbable. When only one digital nerve in a finger is cut the two-point discrimination in the denervated area is poor.

The cases of median sutures for which the sensibility in the thumb pulp was better than in the index and middle fingers may reflect the significance of training. When the sensibility is poor in the median region, the patient tends to pick up objects with the thumb and ring finger, thus resorting to use of the radial sensibility on the dorso-ulnar aspect of the thumb. Of the three median innervated digits, the thumb will therefore be the one most frequently used.

The favourable effect of training on sensibility was noted by Bowden (1954) and by Davis (1949), who reported better results for the dominant hand. In the present study there was no evident difference between the right and left hands.

COMPARISON OF 2 PD AND TOUCH

The picking-up test shows directly the functional value of the sensibility. The correspondence between more or less faultless picking-up tests and good two-point discrimination indicates that determination of 2 PD is a reliable means of testing the functional value of the sensibility.

From the present study of a selected series it is evident that there is a certain, if not particularly close, connection between two-point discrimination and touch. (Reservation is made for the inappropriateness of the term "touch" for the quality of sensibility that is tested by von Frey's hair). This does not mean, however, that the threshold for touch represents the functional value of sensibility so well as the 2 PD value. It would appear that a pressure of not more than one gramme must be perceivable before a 2 PD of less than 30 mm is recorded. As the sensibility improves the values for 2 PD and touch will decrease to normal levels—3 mm and 0.3 g, respectively. In other words, in numerical terms the 2 PD values fall approximately 3 times as much as the touch values.

In the comparison between two-point discrimination and touch only the values for the forefinger have been analysed in detail. Extension of this comparison to the thumb shows that in the cases where the 2 PD values for the thumbs were much lower than for the forefingers there was no appreciable difference in the threshold for touch. There is consequently a discrepancy between two-point discrimination and touch; it is not possible, however, to decide which of the two tests provides the more correct impression of the sensibility. From earlier work (Moberg, 1962) it is evident, however, that in general the 2 PD value is the more reliable.

COMPARISON OF 2 PD AND SUDOMOTOR ACTIVITY

In the study of sudomotor activity the values for most of the patients fell within the normal range of variation. In no case was anhidrosis observed. Considered as a whole, the data are suggestive of hypohidrosis, but in the individual case the sudomotor activity does not provide an objective index of the tactile gnosis.

Above 45 years of age the sweat secretion was usually so low that in only exceptional cases did it permit of quantitative examination; practically all the known methods of stimulating the palmar sweating were tested, though with little effect. This low intensity of palmar sweating in older persons has been observed by several workers (Burch *et al.*, 1942; Mackinnon, 1954; Brun & Dominé, 1958).

It should be stressed that the independence of sweating of the functional value of sensibility applied to cases with long follow-up periods. In nerve injuries in which no appreciable regeneration has taken place the sweat tests are of great value; they are objective and may be of decisive importance in, for example, distinguishing between complete and incomplete nerve injuries.

Owing to the misdirection of outgrowing nerve fibres, recovery of the refined discriminatory sensory function probably requires not only a satisfactory peripheral regeneration but also some measure of central re-organization. It seems likely that the regenerated sweat function reflects the degree of re-innervation rather than any central nervous readjustment. This may explain the absence of a definite relationship between the 2 PD values and sweat indices. It does not account for the occurrence of local hypohidrosis combined with good sensory recovery. Moreover, some reservation is necessary owing to the different fibre diameters. It is possible that the thin sympathetic nerve fibres will regain their function more readily than the larger sensory fibres.

PRIMARY AND SECONDARY NERVE SUTURES

Opinions differ on whether primary or secondary nerve sutures are preferable. Seddon (1944, 1948) was a strong advocator of early secondary sutures; a preference that he justified on the grounds that it is difficult to determine the extent of the damage and ischaemia immediately after an injury (Blackwood & Holmes, 1954). There is a smaller risk of infection at reoperation and it is easier to suture in the then thickened nerve sheath. Seddon also referred to a follow-up study performed by Zachary & Holmes (1946), which, however, demonstrated little more than that immediate suturing is to no advantage.

Most workers are probably now agreed that in war and laceration injuries, sutures should preferably be done after the initial wound has healed. For clean transection injuries which are treated without delay many prefer primary sutures, however (Rank & Wakefield, 1953; Iselin, 1955; Ender *et al.*, 1956; Flatt, 1959).

The present results also suggest that there is no reason why primary sutures should not be performed in the case of clean transections, a choice that has obvious advantages from other aspects.

SUMMARY

The purpose of this investigation was to study the regeneration of sensibility following nerve sutures in the hand performed under favourable conditions—ideal nerve sutures—and to examine whether in such cases there is any relationship between sudomotor activity and sensibility. For such a comparison quantitative evaluations of both functions are required.

The investigation was restricted to the two terminal phalanges, since the pulps are the most important tactile surfaces of the hand.

The recovery of sensibility was measured by examining touch (by von Frey's hair test), tactile gnosis (by Moberg's picking-up test, the five-object test and two-point discrimination), and sweat secretion (by Dole & Thaysen's starch-iodine printing method).

Of these tests the examination of *two-point discrimination* (2 PD) is the most useful, in that it provides a reliable measure of the functional value of sensibility and is applicable to all surafaces. The test was performed by the standard technique, but new principles were applied in the analysis of the results: the same number of trials with one and two compass points was performed; the number of correct answers for two-point stimuli was reduced by the number of wrong answers to one-point stimuli. The threshold was taken as the distance apart of the compass points when 50 per cent of the "reduced" answers to two-point stimuli were correct. This threshold was obtained by the probit procedure. When the test of 2 PD was repeated after 6—12 months the new values were in extremely close agreement with the original values; this would suggest that the principles of calculation applied were correct.

Sudomotor activity was measured quantitatively by comparing the number of simultaneously active sweat glands on symmetrical areas of the pulps of corresponding fingers of each hand (sweat index). Dole & Thaysen's iodine-starch printing method was used for recording the number of active sweat glands. The iodizing technique was modified and an apparatus was designed which enabled the series of prints of a pair of fingers to be taken simultaneously.

Before the technique was applied to the cases of nerve sutures a number of tests were performed on normal subjects. An effective way of stimulating palmar sweating was to discuss sensitive topics with the subject while the prints were being taken; in some cases a better effect was obtained by interrupting the circulation of one arm by means of a blood pressure cuff. Ischaemia in the arm lasting 5—8 minutes did not reduce the number of active sweat glands on the ischaemic hand. In fact there was an increase, and to the same extent on both hands. The results were unaffected by slight inequality in pressures or slight deviations

from symmetry of the pulp areas, provided that the areas near the flexor creases were avoided. When the finger-tips were affixed to the support by, for instance, a strip of adhesive tape, it was found that pressure due to slipping could cause ischaemia in the pulp which resulted in a considerable reduction in the number of dots registered.

The normal variations in the sweat index examined on 50 normal pairs of fingers was found to lie within the approximate limits $\frac{2}{3}$—$\frac{3}{2}$.

The sweat secretion was often found to be greatly depressed by trauma or infection of the finger. This effect was observed on the adjacent digits as well as the test finger. On the other hand, there was no observable anhidrosis as is seen after a peripheral nerve injury.

In 3 cases the individual sweat gland activity was followed by a series of prints in which each dot was identified. In one case of low secretion only one gland was found to secrete continuously, while in another case with quite intense secretion two-thirds of all the active glands were secreting continuously.

The *follow-up examination* was performed on 32 median nerve sutures, 17 ulnar nerve sutures and 22 cases of digital nerve sutures, collected from different sections of hand surgery. The following criteria were applied in the selection of these "ideal" cases: clean transection injury, injury distal to the middle of the forearm, little residual restriction of mobility, no infection, an interval of not more than 6 months between injury and suture, no tension in the suture line, the operation performed by surgeons experienced in the field, a follow-up period of at least 5 years for adults and 4 years for children.

Judged on the basis of the subjective assessment of the results by the patient, complete regeneration of sensibility was recorded in 13 cases less than 11 years old on the occasion of suture (5 median, 4 ulnar and 4 digital nerve sutures). In 12 of the 13 cases the 2 PD value did not exceed 5.5 mm. In the other 56 cases the assessments of subjective symptoms varied considerably and there was apparently no direct relation between them and the results of the tests, beyond the fact that patients with severe symptoms displayed poor test results.

Judged on the basis of the two-point discrimination the regeneration of sensibility was evaluated as follows. Ideal sutures performed from 3 to 6 years of age all showed excellent regeneration of sensibility. The recovery of sensibility decreased with age; in general, the regained 2 PD value expressed in millimetres was the same as the age of the patient, up to 20 years. Between 20 and 31 years the recovery varied, but tended to be poor. Above this age all median and ulnar nerve sutures showed poor functional recovery of sensibility (2 PD near or above 30 mm), good results for digital nerve sutures were, however, recorded up to 50 years or so.

There was no evident difference between the median and ulnar nerve sutures or between primary and secondary operations.

The sensibility recovered fairly uniformly in the previously denervated territories. In some cases of median nerve suture, however, the thumb regained better sensibility than the index finger, and

was never worse. This seems to reflect the favourable effect of training on the regeneration of sensibility.

All cases regained some level of sudomotor activity.

There was a certain tendency to hypohidrosis in all three types of nerve sutures, but in the individual case no correlation could be established between the functional value of the sensibility and the sweat secretion in these cases of ideal sutures.

REFERENCES

Berry, C. M., Grundfest, H. & Hinsey, J. C.: The electrical activity of regenerating nerves in cat. *J Neurophysiol 7*:103, 1944.

Berry, C. M. & Hinsey, J. C.: The recovery of diameter and impulse conduction in regenerating nerve fibres. *Ann NY Acad Sci 117*:559, 1946.

Bishop, G. H.: Neural mechanisms of cutaneous sense. *Physiol Rev 26*:77, 1946.

— The relation of nerve fibre size to modality of sensation. *In* W. Montagna: Advances in biologi of skin. Vol. 1. Cutaneous innervation. Pp 88—98. Pergamon Press, Oxford, 1960.

Björkesten, G.: Suture of war injuries to peripheral nerves. Clinical studies of results. *Acta Chir Scand* Suppl. 119, 1947.

Blackwood, W. & Holmes, W.: Histopathology of nerve injury. *In* H. J. Seddon (Ed.): Peripheral nerve injuries. Medical research council special report series No. 282. Pp. 88—134. Her Majesty's Stationery Office, London, 1954.

Bliss, C. I.: The method of probits. *Science 79*:38, 409, 1934.

Blix, M.: Experimentelle Beiträge zur Lösung der Frage über die specifische Energie der Hautnerven. *Z Biol 20*: 141, 1884 and *21*: 145, 1885.

Boring, E. G.: Cutaneous sensation after nerve-division. *Quart J Exp Physiol 10*: 1, 1916.

Bowden, R. E. M.: Factors influencing functional recovery. *In* H. J. Seddon (Ed.): Peripheral nerve injuries. Medical research council special report series No. 282. Pp. 298—353. Her Majesty's Stationery Office, London, 1954.

Broman, T.: Om tekniken vid den kliniska sensibilitetsundersökningen. *Svensk Läkartidn. 42*: 2205, 1945 A. (Swedish).

— Can a refined method be of importance in clinical investigations of sensibility? *Nord Med 27*: 1801, 1945 B. (Swedish).

Brun, R. & Dominé, E.: Étude sur la transpiration. *Acta Dermatovener 38*: 91, 1958.

Bunnell, S.: Surgery of the nerves of the hand. *Surg Gynec Obstet 44:* 145, 1927.

— Surgery of the hand, p. 317. J. B. Lippincott Co., Philadelphia, 1948.

Burch, G. E., Cohn, A. E. & Neumann, C.: A study of the rate of water loss from the surfaces of the finger tips and toe tips of normal and senil subjects and patients with arterial hypertension. *Amer Heart J 23:* 185, 1942.

Burn, J. H., Finney, D. J. & Goodwin, L. G.: Biological standardization. Oxford University Press, London, 1950.

Cajal, S. R.: Degeneration and regeneration of the nervous system. Hafner Publishing Co., New York, 1928.

Cauna, N.: Nature and functions of the papillary ridges of the digital skin. *Anat Rec 119:* 449, 1954.

Collins, K. J., Sargent, F. & Weiner, J. S.: The effect of arterial occlusion on sweat gland responses in the human forearm. *J Physiol (Lond) 148:* 615, 1959.

Davis, D. R.: Some factors affecting the results of treatment of peripheral nerve injuries. *Lancet* 877, 1949.

Dieden, H.: Klinische und experimentelle Studien über die Innervation der Schweissdrüsen. *Deutsch Arch Klin Med 117:* 180, 1915.

Dole, V. P. & Thaysen, J. H.: Variation in the functional power of human sweat glands. *J Exp Med 98:* 129, 1953.

Edshage, S.: Personal communication.

Ehalt, W.: Behandlungsergebnisse von Verletzungen peripherer Nerven. *In* Bericht über den VIII internationalen Kongress für Unfallmedizin und Berufskrankheiten, Frankfurt a. M. Pp. 419—440, 1938.

Elkington, J. S. C.: Prognosis of peripheral nerve injuries. *Proc Roy Soc Med 37:* 547, 1944.

Ender, J., Krotschek, H. & Simon-weidner, R.: Die Chirurgie der Handverletzungen. Springer-Verlag, Wien, 1956.

Fabritius.: Ueber das Verhalten der Sensibilität in der Blutleere. *Mschr Psychiat Neurol 31:* 1, 1912.

Flatt, A. E.: The care of minor hand injuries. The C. V. Mosby Co., St. Louis, 1959.

Foerster, O.: Die Symptomatologie und Therapie der Kriegsverletzungen der peripheren Nerven.

Verh Ges Deutsch Nervenärzte. Pp. 32—172, 1917.

— Die Symptomatologie der Schussverletzungen der peripheren Nerven. *In* M. Lewandowsky: Handbuch der Neurologie. Verlag von Julius Springer, Berlin, 1929.

FORD, F. R. & WOODHALL, B.: Phenomena due to misdirection of regenerating fibres of cranial, spinal, and autonomic nerves. *Ann Surg 36:* 480, 1938.

VON FREY, M.: Beiträge zur Physiologie des Schmerzsinns. *Ber Sächs Ges Wiss 46:* 283, 1894.

— Beiträge zur Sinnesphysiologie der Haut. *Ber Sächs Ges Wiss 47:* 168, 1895.

— Untersuchungen über die Sinnesfunction der menschlichen Haut. Druckempfindung und Schmerz. *K Sächs Ges Wiss 23:* 175, 1896.

GASSER, H. S. & ERLANGER, J.: The rôle of fibre size in the establishment of a nerve block by pressure or cocaine. *Amer J Physiol 88:* 581, 1929.

GOLDBERG, L.: Personal communication.

GUILFORD, J. P. & LOVEWELL, E. M.: The touch spots and the intensity of the stimulus. *J Gen Psychol 15:* 149, 1936.

GUTMANN, E.: Factors affecting recovery of motor function after nerve lesions. *J Neurol Psychiat 5:* 81, 1942.

— Die funktionelle Regeneration der peripheren Nerven. P. 207. Akademie-Verlag, Berlin, 1958.

— & GUTTMANN, L.: Factors affecting recovery of sensory function after nerve lesions. *J Neurol Psychiat 5:* 117, 1942.

—, GUTTMANN, L., MEDAWAR, P. B. & YOUNG, J. Z.: The rate of regeneration of nerve. *J Exp Biol 19:* 14, 1942.

GUTTMANN, L.: Die nervösen Leitungsbahnen der Schweissekretion beim Menschen. *Deutsch Z Nervenheilk 107:* 61, 1929.

— Die Schweissekretion des Menschen in ihren Beziehungen zum Nervensystem. *Z Neurol Psychiat 135*: 1, 1931.

— & LIST, C. F.: Zur Topik und Pathophysiologie der Schweissekretion. *Z Ges Neurol Psychiat 116:* 504, 1928.

HAGEN, E., KNOCHE, H., SINCLAIR, D. C. & WEDDELL, G.: The role of specialized nerve terminals in cutaneous sensibility. *Proc Roy Soc (Biol) 141:* 279, 1953.

HALDBO, H.: Posttraumatisk Extremitetsdystrofi (Reflexdystrofi). Ejnar Munksgaards Forlag, Copenhagen, 1942. (Danish).

HAMLIN, E. & WATKINS, A. L.: Regeneration in the ulnar, median and radial nerves. Surg Clin N Amer *27:*1052, 1947.

HAWKINS, G. L.: Faulty sensory localization in nerve regeneration. *J Neurosurg 5:* 11, 1948.

HEAD, H. & SHERREN, J.: The consequences of injury to the peripheral nerves of man. *In* H. Head: Studies in neurology. Oxford University Press, London, 1920.

HERRMANN, F., PROSE, P. H. & SULZBERGER, M. B.: Studies on sweating. *J Invest Derm 18:* 71, 1952.

HERZ, E., GLASER, G., MOLDAVER, J. & HOEN, T. I.: Electrical skin resistance test in evalution of peripheral nerve injuries. *Arch Neurol Psychiat 56:* 365, 1946.

HIGHET, W. B.: Procaine nerve block in investigation of peripheral nerve injuries. *J Neurol Psychiat 5:* 101, 1942.

— *In* Highet, W. B. & Holmes, W.: Traction injuries to the lateral popliteal nerve and traction injuries to peripheral nerves after sutur. *Brit J Surg 30:* 212, 1943.

HIGHET, W. B. & SANDERS, F. K.: The effects of stretching nerves after suture. *Brit J Surg 30:* 355, 1943.

HÖGLUND, G. & LINDBLOM, U.: The discharge in single touch receptors elicited by defined mechanical stimuli. *Acta Physiol Scand 52:* 108, 1961.

HOLMES, W. & YOUNG, J. Z.: Nerve regeneration after immediate and delayed suture. *J Anat 77:* 63, 1942.

HUTCHINSON, J., TOUGH, J. S. & WYBURN, G. M.: Comparison of the cutaneous sensory pattern of different regions of the body. *Brit J Plast Surg 1:* 131, 1948.

ISELIN, M.: Chirurgie de la main. Masson et Cie, Paris, 1955.

JÜRGENSEN, E.: Mikrobeobachtungen der Schweissekretion der Haut des Menschen unter Kontrastfärbung. *Arch Klin Med 144:* 193, part 1, 1924, *144:* 248, part 2.

KAPLAN, E. B.: Functional and surgical anatomy of the hand. J. B. Lippincott Co., Philadelphia, 1953.

KLAR, E.: Über Nervenverletzungen an Arm und Hand. Unfallchirurgische Tagung in Heidelberg am 7. und 8. Jan. 1955, P. 31.

KNUDSEN, E. A.: Svedretentionssyndromet. *Nord Med 43:* 1465, 1961. (Danish).

KUNO, Y.: Human perspiration. Charles C. Thomas Publ., Springfield Ill., 1956.

LARSEN, R. D. & POSCH, J. L.: Nerve injuries in the upper extremity. *Arch Surg 77:* 469, 1958.

LINDBLOM, U.: Excitability and functional organization within a peripheral tactile unit. *Acta Physiol Scand 44,* Suppl. 153, 1958.

LOBITZ, W. C. & OSTERBERG, A. E.: Chemistry of palmar sweat. II. Chloride. *Arch Derm & Syph 56:* 462, 1947.

LYONS, W. R.: *In* B. Woodhall & G. W. Beebe (Ed.): Peripheral nerve regeneration. P. 245. U. S. Government Printing Office, Washington 25, D. C., 1956.

MACKINNON, P. C. B.: Variations with age in the number of active palmar digital sweat glands. *J Neurol Neurosurg Psychiat 17:* 124, 1954.

MANNERFELT, L.: Evaluation of functional sensation of skin grafts in the hand area. *Brit J Plast Surg 15:* 136, 1962.

MARBLE, H. C., HAMLIN, E. & WATKINS, A. L.: Regeneration in the ulnar, median and radial nerves. *Amer J Surg 55:* 274, 1942.

Mc DOUGALL, W.: Cutaneous sensation. Reports of the Cambridge Anthropological expedition to Torres Straits, Cambridge, vol. II, part 2. P. 189, 1903.

MIDANA, A.: L' influenza dell'età sulla rigenerazione dei nervi periferici. *Arch Sci Med 54:* 774, 1930.

MINOR, V.: Ein neues Verfahren zu der klinischen Untersuchung der Schweissabsonderung. *Deutsch Z Nervenheilk 101:* 302, 1928.

MOBERG, E.: Discussion. *J Bone Joint Surg 36A*: 305, 1954.

— Objective methods for determining the functional value of sensibility in the hand. *J Bone Joint Surg 40B:* 454, 1958.

— Evaluation of sensibility in the hand. *Surg Clin N Amer 40:* 357, 1960 A.

— Examination of sensory loss by the ninhydrin printing test in Volkmann's contracture. *Bull Hosp Joint Dis 21*: 296, 1960 B.

— Criticism and study of methods for examining sensibility in the hand. *Neurology 12:* 8, 1962.

NICHOLSON, O. R. & SEDDON, H. J.: Nerve repair in civil practice. *Brit Med J 2:* 1065, 1957.

NOORDENBOS, W.: PAIN. Problems pertaining to the transmission of nerve impulses which give rise to pain. Elsevier Publishing Co., Amsterdam, 1959.

— On the specificity of sensory events. *Psychiat Neurol Neurochir 63:* 298, 1960.

ODÉN ,S. & HOFSTEN, B. von: Detection of fingerprints by the ninhydrin reaction. *Nature 173:* 449, 1954.

OESTER, Y. T. & DAVIS, L.: Recovery of sensory function. *In* B. Woodhall & G. W. Beebe. (Ed.): Peripheral Nerve Regeneration. Pp. 241—309, U. S. Government Printing Office, Washington 25, D. C., 1956.

POLLOCK., L. J.: & DAVIS, L.: Peripheral nerve injuries. *Amer J Surg 15:* 411 & 571, 1932.

PONTEN, B.: Grafted skin. Observations on innervation and other qualities. *Acta Chir Scand* Suppl. 257, 1960.

RANDALL, W. C.: Quantitation and regional distribution of sweat glands in man. *J Clin Invest 25:* 761, 1946 A.

— Sweat gland activity and changing patterns of sweat secretion on the skin surface. *Amer J Physiol 147:* 391, 1946 B.

—, DEERING, R. & DOUGHERTY, I.: Reflex sweating and the inhibition of sweating by prolonged arterial occlusion. *J Appl Physiol 1:* 53, 1948.

— & Mc CLURE, W.: Quantitation of the output of individual sweat glands and their response to stimulation. *J Appl Physiol 2:* 72, 1949.

RANK, B. K. & WAKEFIELD, A. R.: Surgery of repair as applied to hand injuries. E. & S. Livingstone Ltd, Edinburgh and London, 1953.

SAKELLARIDES, H.: A follow-up study of 172 peripheral nerve injuries in the upper extremity in civilians. *J Bone Joint Surg 44A:* 140, 1962.

SARGENT, P. & CAMB, B. C.: Discussion on the end-results of injuries to the peripheral nerves treated by operation. *Brit Med J* II. P. 464, 1920.

SEDDON, H. J.: The early management of peripheral nerve injuries. *Practitioner 152:* 101, 1944.

— War injuries of peripheral nerves. *Brit J Surg* War suppl. 2. P. 325, 1948.

— (Ed.): Peripheral nerve injuries. Medical research council special report series No. 282. Pp. 1—15. Her Majesty's Stationery Office, London, 1954.

—, MEDAWAR, P. B. & SMITH, H.: Rate of regeneration of peripheral nerve injuries in man. *J Physiol 102:* 191, 1943.

Sharpey-schafer, E.: The effects of de-nervation of a cutaneous area. *Quart J Exp Physiol 19:* 85, 1929.

Sherman, I. C., Tigay, E. L., Arieff, A. J. & Schiller, M. A.: Return of sensation after experimentally produced lesions in sciatic nerve of cat. *J Neurophysiol 12:* 1, 1949.

Sinclair, D. C., Weddell, G. & Zander, E.: The relationship of cutaneous sensibility to neurohistology in the human pinna. *J Anat 86:* 402, 1952.

Sperry, R. W.: The problem of central nervous reorganization after nerve regeneration and muscle transposition. *Quart Rev Biol 20:* 311, 1945.

Stopford, J. S. B.: The variation in distribution of the cutaneous nerves of the hand and digits. *J Anat 53:* 14, 1918.

— The results of secondary suture of peripheral nerves. *Brain 43:* 1, 1920.

Stromberg, W. B., Mc Farlane, R. M., Bell, J. L., Koch, S. L. & Mason, M. L.: Injury of the median and ulnar nerves. *J Bone Joint Surg 43A:* 717, 1961.

Sunderland, S.: The intraneural topography of the radial, median and ulnar nerves. *Brain 68:* 243, 1945.

— Observations on course of recovery and late end results in a series of cases of peripheral nerve suture. *Aust New Zeal J Surg 28:* 264, 1949.

— Regeneration phenomena in human peripheral nerves. *In* P. Weiss: Genetic Neurology. University of Chicago Press, Chicago, 1950.

— & Bradley, K. C.: The cross-sectional area of peripheral nerve trunks devoted to nerve fibres. *Brain 72:* 428, 1949.

— & Bradley, K. C.: Denervation atrophy of the distal stump of a severed nerve. *J Comp Neurol 93:* 401, 1950.

Takahara, K.: *In* Y. Kuno: Human perspiration. P. 294. Charles C. Thomas Publ., Springfield, Ill., 1956.

Thorburn, W.: Discussion on the end-results of injuries to the peripheral nerves treated by operation. *Brit Med J* II: 462, 1920.

Trevan, J. W.: The error of determination of toxicity. *Proc Roy Soc 101:* 483, 1927.

Trotter, W. B. & Davies, H. M.: Experimental studies in the innervation of the skin. *J Physiol 38:* 134, 1909.

Walshe, F. M. R.: The anatomy and physiology of cutaneous sensibility. A critical review. *Brain 65*: 48, 1942.

Weber, E. H.: Ueber den Tastsinn. *Arch Anat Physiol wissensch Med.* Pp. 152—160, 1835.

Weddell, G.: The pattern of cutaneous innervation in relation to cutaneous sensibility. *J Anat 75:* 346, 1941 A.

— Multiple innervation of sensory spots in skin. *J Anat 75:* 441, 1941 B.

— The anatomy of cutaneous sensibility. *Brit Med Bull 3:* 167, 1945.

—, Guttmann, L. & Gutmann, E.: The local extension of nerve fibres into denervated areas of skin. *J Neurol Psychiat 4:* 206, 1941.

—, Palmer, E. & Pallie, W.: Nerve endings in mammalian skin. *Biol Rev 30:* 159, 1955.

Weiss, P.: An introduction to genetic neurology. *In* P. Weiss: Genetic neurology. University of Chicago Press, Chicago, 1950.

Woodhall, B. & Beebe, G. W. (Ed.): Peripheral nerve regeneration. A follow-up study of 3 656 World War II injuries. Veterans Administration Medical Monograph. U. S. Government Printing Office, Washington 25, D. C., 1956.

Zachary, R. B.: Results of nerve suture in peripheral nerve injuries. *In* H. J. Seddon (Ed.): Peripheral nerve injuries. Medical research council special report series No. 282. Pp. 354—388. Her Majesty's Stationery Office, London, 1954.

— & Holmes, W.: Primary suture of nerves. *Surg Gynec Obstet 82:* 632, 1946.

Zrubecky, G.: Die Hand. Das Tastorgan des Menschen. Ferdinand Enke Verlag, Stuttgart, 1960.

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